Information Report **March 2002**

Sacramento and San Joaquin River Basins

Comprehensive Study

Existing Hydrodynamic Conditions in the Delta During Floods

The Reclamation Board
State of California

US Army Corps of Engineers
Sacramento District

Existing Hydrodynamic Conditions in the Delta During Floods

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CHAPTER I

INTRODUCTION

BACKGROUND

In January 1997, Californians experienced one of the most geographically extensive and costly flood disasters in the State's history. Major storms throughout the State caused record flows on many rivers. In the Central Valley, the flood management system for the Sacramento and San Joaquin Rivers was stressed to capacity and beyond. The existing flood management system prevented over $21 billion in damages and protected lives during the event. Even so, levees on the Sacramento River and its tributaries sustained two major breaks and were near failure at many locations. On the San Joaquin River, levees failed at more than 24 locations. These failures caused significant damages in both basins.

In response to concerns primarily raised by the 1997 flood, the Governor of California formed the Flood Emergency Action Team (FEAT). In its May 1997 report, the FEAT recommended developing a new master plan for improved flood management in the Central Valley of California. The U.S. Congress and California State Legislature subsequently authorized the Sacramento and San Joaquin River Basins Comprehensive Study (Comprehensive Study). The Reclamation Board of the State of California and the U.S. Army Corps of Engineers Sacramento District (Corps) began work together on the study in 1998 for development and evaluation of a master plan and alternatives to reduce flood damages while integrating ecosystem restoration in the Sacramento and San Joaquin River basins.

The Comprehensive Study is distinguished from other ongoing resource management programs in the Central Valley because of its mission to address both flood damage reduction while integrating ecosystem restoration on a system-wide basis. The problem identification area for the Comprehensive Study consists of the channels and floodplains of the Sacramento and San Joaquin Rivers and the lower reaches of their major tributaries. The Tulare Lake Basin is not included in the problem identification area, although the contribution of flood flows from the Kings River to the San Joaquin River is considered. A broad range of potential measures to reduce flood damages and promote ecosystem restoration was identified through a series of Central Valley outreach meetings and workshops with Federal, State and local agencies, other interested groups, and individuals. Increased river conveyance capacity, increased flood storage, and additional floodplain management are three categories of measures identified to address the flooding problems and integrate ecosystem restoration.

The Comprehensive Study is currently developing concept plans with varying emphases on measures as a preparation step for the development of alternative master plans. To estimate the potential location and frequency of levee failure and resulting flooding, various detailed hydrologic, hydraulic, and economic models were developed to evaluate system-wide performance and to identify problems that may not be evident from historical floods. An ecosystem functions assessment tool is also being developed to couple output from hydraulic models with mapping information to identify how ecosystem conditions could change with alternative master plans.

The Delta is the downstream boundary to the Sacramento and San Joaquin River basins. The hydrodynamic conditions in the Delta are complex due to the interwoven waterways and the endless possibility for combination of the timing and magnitude of tidal ranges and Delta inflows. Due to its downstream location, the Delta may be impacted from upstream improvements on Sacramento and San Joaquin Rivers considered in the Comprehensive Study. An understanding of Delta hydrodynamics during floods is essential for the development of alternative master plans and to evaluate potential impacts and mitigating efforts.

PURPOSE AND SCOPE

The objective of this task order is to evaluate hydrodynamic conditions, controlling factors and flow/stage frequency relationships in the Sacramento-San Joaquin Delta (Delta) during floods. The historical 1997 flood and results from hydrodynamic models are used to illustrate the complex hydrodynamics in the Delta.

The study area is the entire legal Sacramento-San Joaquin Delta, of which the upstream boundaries include Sacramento River at Freeport, San Joaquin River at Vernalis, eastside streams near Stockton, and Yolo Bypass near Sacramento, and the downstream boundary is near Martinez. However, the discussion of simulated Delta hydrodynamics will focus on the areas downstream of project levees. (See Chapter II for the definition of project levees.)

REPORT ORGANIZATION

This information report is organized into seven chapters. Chapter I provides the introduction of the study and its objective; Chapter II describes the basic elements of the Delta hydrodynamics including a summary of available historical data; Chapter III describes the Delta hydrodynamics during the historical 1997 flood; Chapter IV provides an overview of the simulation models used in the Comprehensive Study for the Delta hydrodynamics, and the preparation and applications of these models; Chapter V discusses the Delta hydrodynamics using the results of these simulation models, assuming the baseline hydrology and system-wide operation and levee performance; Chapter VI summarizes the findings of this study; and Chapter VII lists all the references used in preparing this information report. Detailed hydrographs and tabulations of model simulation results are provided in the Appendices.

CHAPTER II

MAJOR FACTORS OF DELTA HYDRODYNAMICS

SUMMARY OF DELTA DEVELOPMENT

Prior to human intervention, the Delta consisted of low-lying vegetated wetlands separated by a complex of rivers, channels and sloughs. Along the waterways were slightly higher over-bank deposits of coarser sediments, commonly referred to as "natural levees." The Delta was reclaimed in two phases. During the first phase (1850-l880), reclamation projects were small-scale efforts using manpower and horsepower to build levees on top of existing natural levees.

In the second phase (from 1880 to the early 1900s), levee building in the Delta was more aggressive and was accomplished with powerful mechanical equipment. Swamp and overflow lands in the Sacramento and San Joaquin River basins were reclaimed through the construction of levees that reduced the discharge of floodwaters into the floodplain. These actions resulted in increasing flows into the Delta. Also during this period, hydraulic mining debris that originated primarily on Sacramento River tributaries raised riverbeds and became deposited in Delta channels. Following decades of study and deliberation, Congress authorized construction of the Sacramento River Flood Control Project, which included widening of the lower Sacramento River into and through the Delta. Later, the Reclamation Board was created and Congress authorized the Central Valley Project (CVP).

The State Water Resources Development Bond Act was approved in 1960, launching the State Water Project (SWP). SWP facilities include levees, control structures, channel improvements, and appurtenant facilities in the Delta that are used for water conservation, water supply, cross-Delta water transfers, and flood and salinity controls. In 1960, the Corps completed the Sacramento River Flood Control Project, which incorporated and improved flood control for a portion of the Delta. In the 1970s, the California Legislature recognized that the Delta levee system benefits many segments and interests of the public and approved a plan to preserve the Delta levee system.

In 1986, the CVP-SWP Coordinated Operation Agreement was initiated and the California Supreme Court confirmed the authority and discretion of the State Water Resources Control Board (SWRCB) over water rights and water quality issues in the Bay-Delta system, including jurisdiction over the Federal CVP. Since the late 1980s, a flurry of regulatory and legislative actions have shaped the future of the Delta. The Delta Flood Protection Act of 1988; Environmental Mitigation and Protection Requirements; the Delta Protection Act; the Central Valley Project Improvement Act (CVPIA); and the Safe, Clean, Reliable Water Supply Act were enacted. In 1994-1995, State and Federal agencies entered into the historic Bay-Delta Accord, and initiated the CALFED Bay-Delta Program. The Delta includes over 700,000 acres, with 700 miles of meandering waterways and approximately 1,100 miles of levees.

MAJOR FACTORS AFFECTING DELTA HYDRODYNAMICS

This section provides a brief discussion on major factors affecting the existing Delta hydrodynamics including tributary inflows, tides, physical configuration of levee and waterways. Most of the waterways in the Delta are under tidal influences that cause river stages to rise and fall typically about twice each day. The physical configuration of the Delta changed along with the developments over the past two centuries. Some major alterations of waterways were made to facilitate CVP-SWP operations and local diversions. Other long-term factors, such as land subsidence and rising sea level, can affect the levee safety and change the Delta hydrodynamics, but they are not included in the following discussion of existing conditions.

Delta Waterways

Delta Tributaries and Distributaries

Major tributaries to the Delta include the Sacramento, the San Joaquin, the Consumnes, the Calavera, and the Mokelumne rivers. The Sacramento River is the largest source of Delta water among all tributaries in both normal and flooding conditions. The Consumnes River is the only tributary that does not have upstream reservoirs operated for flood control purpose. The Yolo Bypass receives floodwater of the Sacramento River from discharges over the Fremont and Sacramento weirs from the Colusa Basin Drain. The Yolo Bypass delivers water back to the Sacramento River through the Cache Slough near Rio Vista.

These tributaries form a network of waterways in the Delta before flowing out to the San Francisco Bay. Major natural distributaries of the Sacramento River in the Delta are the Georgiana Slough and the Three Mile Slough, and for the San Joaquin River are the Paradise Cut, the Old River, and the Middle River. Paradise Cut is hydraulically connected to the San Joaquin River only during high flow conditions.

Man-made Canals

Man-made channels such as the Delta Cross Channel (DCC), the Victoria Canal, and the Grant Line Canal are added into the already complex network of waterways to facilitate the CVP-SWP operation and local diversions. Portions of the Old River and the Middle River have been dredged and altered to enhance the capability of transferring water through the west and central Delta to the CVP-SWP pumping facilities in the south Delta area.

The DCC, a gated channel that connects the Sacrametno River to snodgrass Slough, allows water from the Sacramento River to flow southward through the Delta toward export pumps in the south Delta. The DCC gates are operated in accordance with SWRCB's *Decision 1641* as follows:

- **November 1 through January 31:** Gates will be closed for a total of up to 45 days for fisheries protection as requested by the USFWS, NMFS, and DFG. Gates may be closed on very short notice and may be closed on weekends.

- **February 1 through May 20:** Gates will be closed.

- **May 21 through June 15:** Gates will be closed for a total of 14 days for fisheries protection as requested by the USFWS, NMFS, and DFG. Gates may be closed on very short notice. Whenever possible, gates will be open on the weekends (Saturday and Sunday) and the weekday holiday on Memorial Day weekend, but this cannot be guaranteed.

- **June 16 through October 31:** Gates will generally be open. However, high flows on the Sacramento River, unforeseen fishery protection actions or water quality compliance in the Delta may necessitate a short-term closure.

In addition to the requirements of *Decision 1641*, U.S. Bureau of Reclamation (USBR) standing operation procedures call for gate closure when flow on the Sacramento River reaches the range of 20,000 to 25,000 cfs. Thus, under most flooding conditions, the DCC is closed and the Sacramento River is connected to the San Joaquin River through the Three Mile Slough and the Georgiana Slough upstream from their confluence.

Flow Barriers

In recent years, temporary barriers have been installed in the Old River, the Middle River, and the Grant Line Canal during spring months for water quality reasons and fishery protection. Although these barriers can affect the Delta hydrodynamics, they are generally not in place during flood seasons.

DWR is currently undergoing the South Delta Improvement Program (SDIP) that includes physical changes in the Delta waterways such as flow control structures on the Old River and Middle River, a fish control structure at the head of the Old River, dredging of the Old River, and a new intake for the Clifton Court Forebay. These permanent structures will alter the Delta hydrodynamics, especially in the south Delta area. However, they are still in the design phase and thus, information regarding physical configurations or operational criteria are limited. According to the project description, the design of flow control structures will allow flows to pass freely during the periods of natural or regulated high flow, when water levels are maintained without the need for flow control.

Tidal Influences

Tides are the alternating rise and fall in sea level with respect to the land produced by the gravitational attraction of the sun and the moon. The alternation of high and low tides, roughly twice a day, is caused by the daily (or diurnal) rotation of the earth with respect to the direction of combined lunar and solar gravitational forces. The difference in the height between consecutive high and low tides is known as the range of tides. In addition to astronomical factors, localized factors such as ocean-floor topography, configuration of the coastline, and other hydrographic influence can affect the observed range and arrival time of tides.

Astronomical Effects

To facilitate the discussion in later chapters, three major astronomical effects that govern the tidal range and arrival time at any location are summarized as follows.

- **Lunar Phase Effect**: The lunar phase effect is caused by the moon's changing position with respect to the earth and sun during the monthly cycle of phases (29.53 days) and the resulting gravitational attractions of the moon and of the sun may variously act along a common line or at changing angles relative to each other. This effect creates spring tides during new moon and full moon, and neap tides during the first and third quarters.

- **Parallax Effect**: The parallax effect is caused by the changing distances between the earth and the moon during a month, and the earth and the sun during a year. The moon's orbit is in elliptic shape. Once each month, when the moon is closest to the earth (perigee), the lunar tide-generating force will be higher than usual and the tidal ranges will be greater than average. Approximately two weeks later, when the moon is farthest from the earth (apogee), the lunar tide-generating force will be lower than usual, and the tidal ranges will be less than average. Similarly, tidal ranges will be enhanced when the earth is closest to the sun (perihelion), about January 2 of each year, and reduced when the earth is farthest from the sun (aphelion), around July 2 of each year.

- **Lunar Declination Effect:** The plane of the moon's orbit is inclined about 5° to the plane of the earth's orbit (the ecliptic) and thus, the moon's monthly revolution around the earth remains very close to the ecliptic. The ecliptic is inclined 23.5° to the earth's equator, north and south of which the sun moves once each half year to produce the seasons. Therefore, the moon passes from a position of maximum angular distance north of the equator to a position of maximum angular distance south of the equator during each half-month. The changing angular distance of the moon above or below the equator causes the difference between the heights of two daily tides of the same phase. This phenomenon is known as diurnal inequality.

Tidal Influence in the Delta

Ground elevations in the Bay-Delta system vary from at or near sea level in the San Francisco Bay area to 10 feet and more in the Sacramento area. Tidal influence is prominent in the Delta, especially in the west and central Delta. Its influence diminishes in the far northeast and southeast reaches of the Delta. Table II-1 shows the approximate daily tidal fluctuations at selective locations in the Delta.

TABLE II-1

DAILY TIDE FLUCTUATIONS AT SELECTIVE LOCATIONS IN THE DELTA

Tide Gage Station Location	Approximate Daily Tide Fluctuation (feet)
Martinez	5.6
Rio Vista	4.8
Roaring River	4.4
Mallard Island	5.1
Antioch	4.3
Tracy	3.0
Venice Island	3.8
Freeport	1.7
Thornton	1.5
"I" Street Bridge	1.1
"H" Street Bridge	0.0
Source: CALFED, *Levee System Integrity Program Plan*, July 2000.	

During rising tides, strong tide currents may create reverse flows (land-ward flows) in some Delta waterways. The magnitude of reverse flows, however, is dependent upon other factors such as Delta tributary inflows, CVP-SWP operations and local pumping. The river stage at Martinez, in the western portion of the legal Delta, is primarily affected by the tides although it may be affected by major inflows from Delta tributaries as well.

Decisions and alternative evaluations for flood control projects are often linked to a protection level defined by recurrence frequency. However, recurrence frequency is not commonly used to define tidal ranges because tides resulted from gravitational forces and their variations are influenced by planetary movements. The mechanisms that control tidal ranges have little relationship, if any, to the recurrence frequency of surface water hydrology.

Levees

Approximately 385 miles of project levees and 715 miles of non-project levees are located in the legal Delta (Figures II-1 and II-2). "Project levees" are levees that were improved or adopted as part of Federal flood control projects and were constructed to convey floodwaters past developed areas. Most of the project levees in the Delta are along the Sacramento and San Joaquin Rivers and their major distributaries as they enter the Delta. These project levees are included in the study areas of Comprehensive Study. The remaining levees in the Delta are non-project levees that were originally designed and built based on anticipated tidal ranges rather than flood flows.

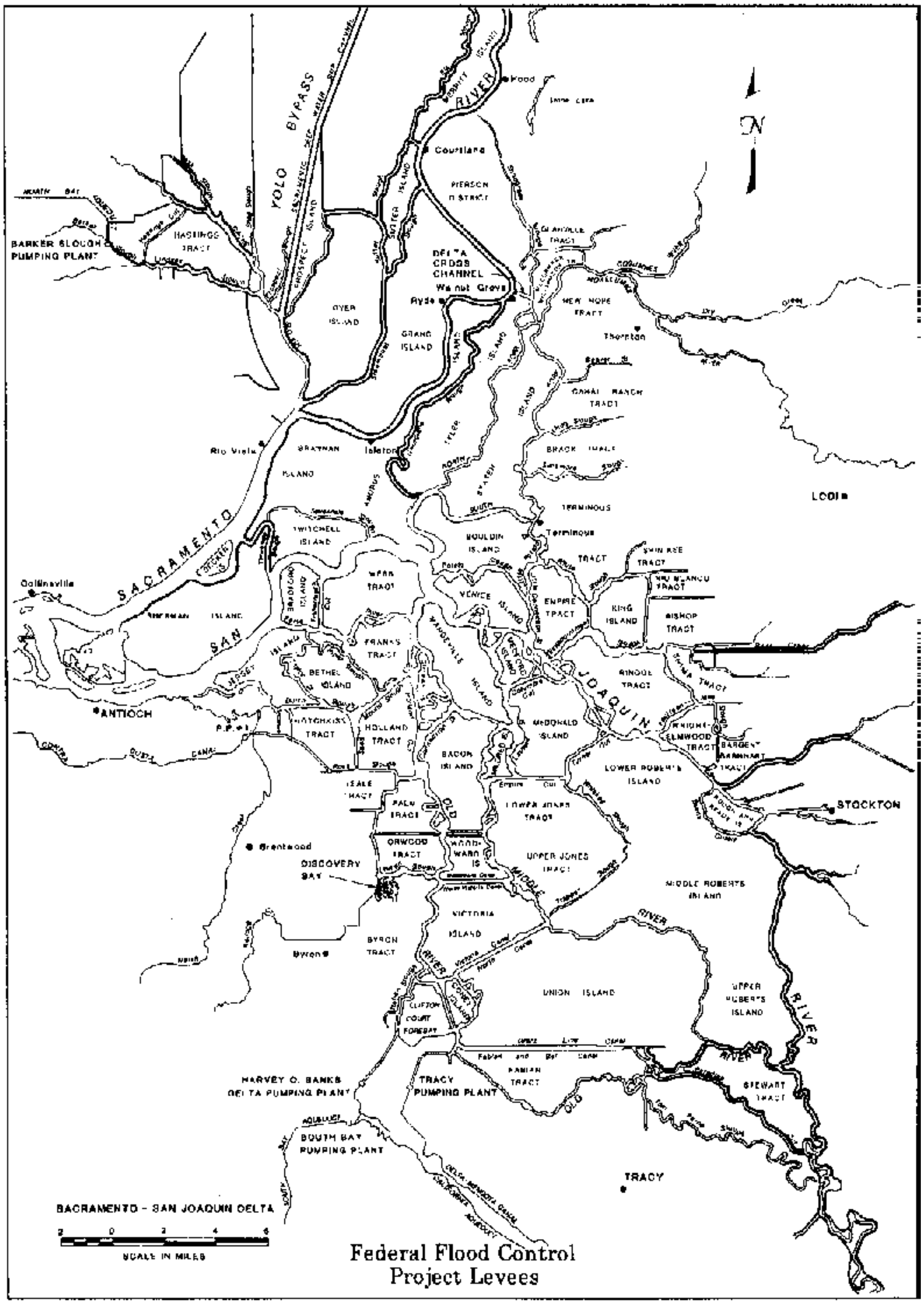
Recognizing the potential benefits to local agricultural practices, water exports, navigation, recreation, and wildlife, the State of California and local agencies have formed a partnership to reconstruct a portion of Delta levees to the Corps' Public Law (PL) 84-99 Delta Specific Standard. The PL 84-99 Standard calls for a 1.5 feet of freeboard above 100-year flood stage for all islands and tracts. The rehabilitation demonstrated its benefit in protecting Delta islands and tracts in the 1997 Flood. CALFED's Delta Levee System Integrity Program continues the levee rehabilitation efforts in the Delta to the PL 84-99 Standard with added ecosystem restoration considerations.

CVP-SWP Operations

Major water diversion facilities in the Delta include pumping plants that provide water to the CVP Delta Mendota Canal, the SWP California Aqueduct, the North Bay Aqueduct and the Contra Costa Canal. Water conveyance from north to south through the Delta to diversion facilities is facilitated by the DCC, Georgiana Slough and Three Mile Slough. In the south Delta, water conveyance to the Tracy (CVP) and Banks (SWP) pumping plants is facilitated through Old River, Middle River and Victoria Canal. Portion of Middle and Old rivers have been dredged to facilitate these exports. Net reverse flows in these channels (toward the east and south) are common when the pumps are active.

In recent years, the operations of CVP and SWP south Delta export facilities are getting more restricted due to increasing water quality and environmental concerns. The excess water in the Delta during flooding conditions provides an opportunity to transfer water to the San Luis Reservoir or to provide interruptible supply (limited amounts) to the SWP contractors without conceivable water quality or environmental impacts. The storage level in the San Luis Reservoir dictates the amount and timing of excess water pumping. Exports during flooding conditions are helpful in alleviating flooding in the south Delta. When operated in full, the combined diversion rate can reach over 10,000 cubic feet per second (cfs), about one half of the Old River peak flow at Bacon Island or one fifth of the San Joaquin River peak flow at Vernalis during the 1997 Flood.

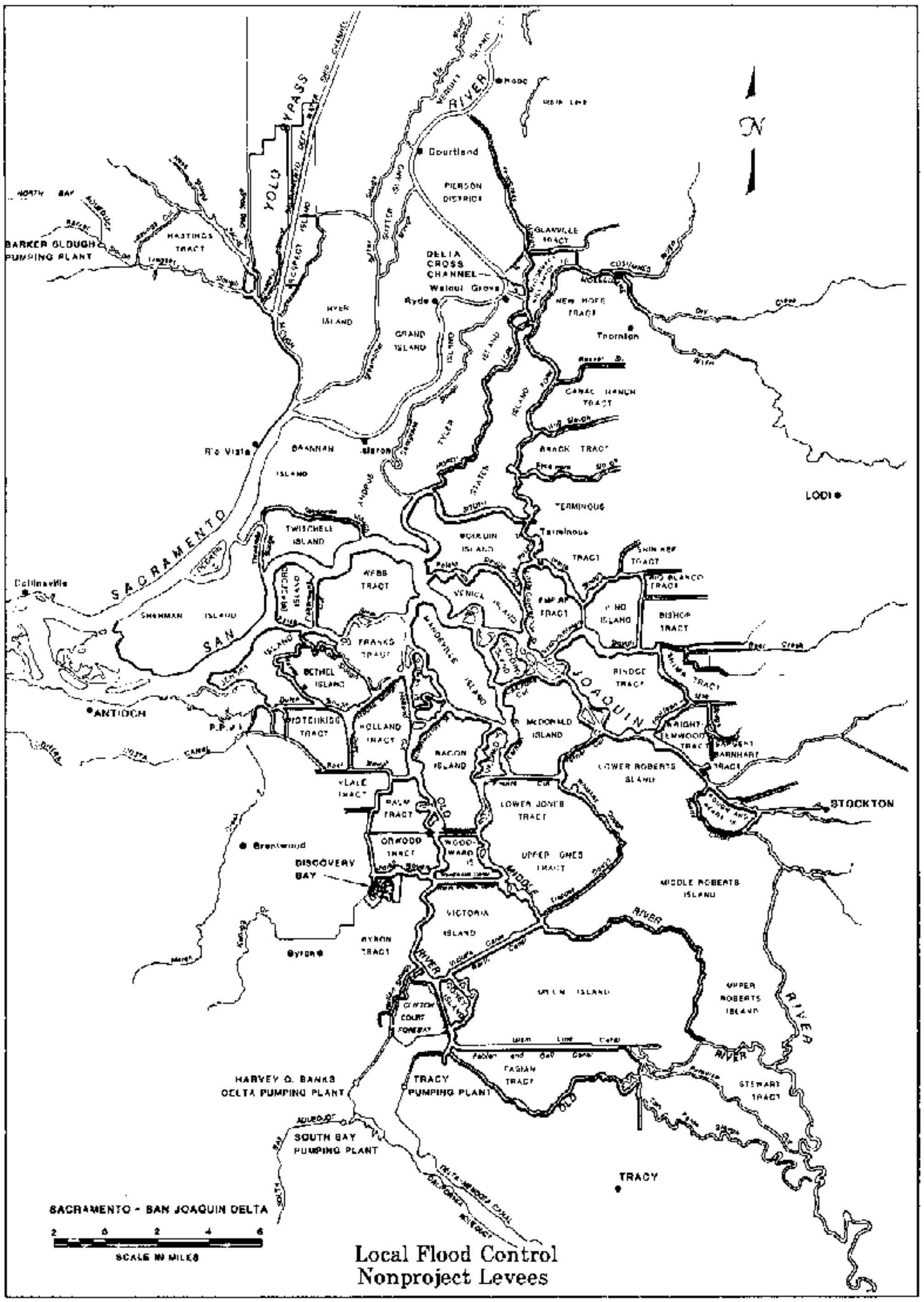
FIGURE II-1
PROJECT LEVEES IN THE DELTA



Sacramento–San Joaquin Delta Atlas
Department of Water Resources

FIGURE II-2

NON-PROJECT LEVEES IN THE DELTA



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AVAILABLE HYDRODYNAMIC DATA FOR THE DELTA

Record Inventory

The DWR Interagency Ecological Program (IEP) has compiled historical hydrodynamic and water quality data of the Bay-Delta tributaries, collected by different agencies at over 120 stations. The participating agencies include Contra Costa Water District (CCWD), California Data Exchange Center (CDEC), California Department of Water Resources (DWR), East Bay Municipal Utility District (EBMUD), National Oceanic and Atmospheric (NOAA), University of California at Berkeley (UCB), USBR, and U.S. Geological Survey (USGS). The length of records ranges from several months (for some short-term monitoring projects) to more than 70 years, and the data are accessible through the IEP website (http://www.iep.ca.gov/). Tables II-2 through II-7 and Figures II-3 through II-8 show the IEP flow and stage stations in the Delta. It is noted that only a few stations have long-term records, and most of them are stage stations.

Flow Splits in the Delta

The Sacramento and San Joaquin Rivers bifurcate at several locations in the Delta. Flow splits in the Delta waterways, if properly defined, are beneficial to flood control programs in forecasting the distribution of floodwater in the Delta under given operational scenarios. However, the definition of a flow-split relationship is highly dependent upon the data availability near the bifurcation.

Sacramento River Flow Split into the Georgiana Slough near Walnut Grove

Two USGS flow gages are available near the bifurcation: Sacramento River north of the Delta Cross Canal (RSAC128) and Sacramento River south of the Georgiana Slough (RSAC123). Concurrent records are available in periods during December 1995 through July 1999. When the Sacramento River flow exceeds 25,000 cfs, USBR generally closes the Delta Cross Canal gates and thus, the Georgiana Slough flow can be estimated by the flow difference at these two stations. Figure II-9 shows the scatter plots of the estimated Georgiana Slough flows and the historical Sacramento River flows above 25,000 cfs. These records suggest that in average, the Georgiana Slough receives about 28 percent of the flow in the Sacramento River with an error range of 2,000 cfs.

The 28 percent of flow split is consistent to the Sacramento River-Georgiana Slough flow split in DWR's DAYFLOW program, which is used for calculating daily water balance in the Delta for CVP-SWP operations and compliance of water quality and environmental standards. Based on a regression analysis conducted in 1978, DAYFLOW assumes the Georgiana Slough flow to be about 22 percent of Sacramento River flow at I Street when the Delta Cross Canal is closed. It is noted that the flow in Sacramento River at I Street splits into Steamboat Slough before reaching the USGS gage upstream from the Delta Cross Canal.

TABLE II-2

IEP FLOW STATIONS IN THE WEST DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	CRGRV002	DWR	575332 4230246	38-13-08 122-08-22	DWR-ESO S10, Green Valley Creek at Green Valley Rd
2	CRSUS004	DWR	578244 4230920	38-13-29 122-06-22	DWR-ESO S15, Suisun Creek at Cordelia Rd
3	DOM	USGS	608500 4212500		USGS Delta Outflow Monitoring, averaged of stations around
4	LSHL001	USGS	605358 4212207	38-03-12 121-47-57	USGS SHERLN, Sacramento River at Sherman Lake
5	LSHL003	USGS	606615 4209326	38-01-38 121-47-07	USGS ADCP study, San Joaquin River at Mayberry Cut
6	NDOI	CDEC	608500 4213000		CDEC Delta Outflow Index, averaged of stations around
7	RSAC084	USGS	602952 4213564	38-03-57 121-49-35	USGS SACSHL, Sacramento River
8	RSAN002	USGS	601475 4210802	38-02-28 121-50-37	USGS SJR-NY, Mouth of San Joaquin River
9	RSAN003	USGS	602450 4210876	38-02-30 121-49-57	USGS ADCP study, San Joaquin River at Sherman Lake
10	SLMAY002	USGS	607555 4210109	38-02-03 121-46-28	USGS MAY-SL, Mayberry Slough
11	SLMID001	USGS	600570 4211037	38-02-36 121-51-14	USGS ADCP study, Middle Slough at Winters Island
12	SLMZU032	USGS	599265 4214135	38-04-17 121-52-06	USGS MON-SL, Montezuma Slough
13	SLNY002	USGS	600245 4209708	38-01-53 121-51-28	USGS NY-SL, New York Slough

FIGURE II-3

IEP FLOW STATIONS IN THE WEST DELTA

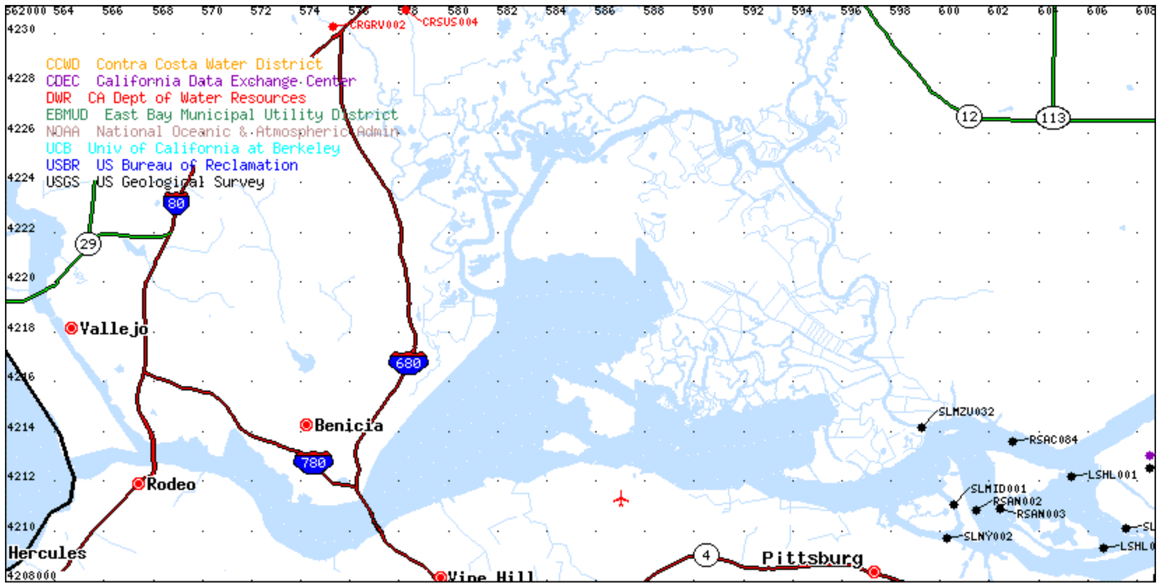


TABLE II-3

IEP STAGE STATIONS IN THE WEST DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	RSAC045	USGS	566675 4212354	38-03-30 122-14-24	USGS 182130, Selby (Wickland Oil Pier)
2	RSAC054	CDEC	575655 4209067	38-02-80 122-13-80	CDEC MRZ, DWR-ESO 40, USGS 182450, Sacramento River at Martinez
3	RSAC054	DWR	575650 4209073	38-01-41 122-08-17	CDEC MRZ, DWR-ESO 40, USGS 182450, Sacramento River at Martinez
4	RSAC054	UCB	575650 4209073	38-01-41 122-08-17	CDEC MRZ, DWR-ESO 40, USGS 182450, Sacramento River at Martinez
5	RSAC054	USGS	575529 4209041	38-01-40 122-08-22	CDEC MRZ, DWR-ESO 40, USGS 182450, Sacramento River at Martinez
6	RSAC075	CDEC	594888 4211206	38-05-00 121-85-00	CDEC MAL, DWR-CD 3355, Sacramento River at Pittsburgh
7	RSAC075	DWR	594888 4211206	38-05-00 121-85-00	CDEC MAL, DWR-CD 3355, Sacramento River at Pittsburgh
8	RSAC081	DWR	600432 4214396	38-04-25 121-51-18	DWR-CD 1110, DWR-ESO C02, USBR CLV/CVB, Sacramento River at Collinsville, mouth of San Joaquin River
9	RSAC081	USBR	600796 4214462	38-04-27 121-51-03	DWR-CD 1110, DWR-ESO C02, USBR CLV/CVB, Sacramento River at Collinsville, mouth of San Joaquin River
10	RSAN007	CDEC	605190 4208259	38-01-04 121-48-06	CDEC ANH, DWR-CD 5020, San Joaquin River at Antioch between lights 7 & 8
11	RSAN007	DWR	605190 4208259	38-01-04 121-48-06	CDEC ANH, DWR-CD 5020, San Joaquin River at Antioch between lights 7 & 8
12	SLCBN001	DWR	581236 4225956	38-10-47 122-04-21	DWR-ESO S20, Chadbourne Slough at Wells/Hollywood Club
13	SLCBN002	CDEC	580310 4226533	38-18-50 122-08-30	CDEC SNC, DWR-ESO S21, Chadbourne Slough at Sunrise Club
14	SLCBN002	DWR	580357 4226287	38-10-58 122-04-57	CDEC SNC, DWR-ESO S21, Chadbourne Slough at Sunrise Club
15	SLCRD000	DWR	580213 4221045	38-08-08 122-05-05	DWR-ESO S34, Cordelia Slough at Miramonte
16	SLCRD003	DWR	579757 4222952	38-09-10 122-05-23	DWR-ESO S33, Cordelia Slough at Cygnus
17	SLCRD006	CDEC	577732 4223425	38-09-26 122-06-46	CDEC IBS, DWR-ESO S97, Cordelia Slough at Ibis
18	SLCRD006	DWR	577732 4223425	38-09-26 122-06-46	CDEC IBS, DWR-ESO S97, Cordelia Slough at Ibis
19	SLCRD009	DWR	577693 4224935	38-10-15 122-06-47	DWR-ESO S98, Cordelia Slough at Garibaldi
20	SLGYR003	CDEC	579332 4219088	38-11-80 122-09-50	CDEC GYS, DWR-ESO S35, Goodyear Slough at Morrow Island
21	SLGYR003	DWR	579355 4219187	38-07-08 122-05-41	CDEC GYS, DWR-ESO S35, Goodyear Slough at Morrow Island
22	SLMZU003	DWR	583087 4223355	38-09-22 122-03-06	DWR-ESO S54, Montezuma Slough at Hunter Cut
23	SLMZU011	CDEC	590292 4226860	38-18-70 121-96-90	CDEC BDL, DWR-ESO S49, Montezuma Slough at Beldons
24	SLMZU011	DWR	590229 4226853	38-11-13 121-58-11	CDEC BDL, DWR-ESO S49, Montezuma Slough at Beldons
25	SLMZU025	DWR	597565 4219755	38-07-20 121-53-13	DWR-ESO S64, Montezuma Slough at National Steel
26	SLMZU029	DWR	597676 4216551	38-05-36 121-53-10	DWR-ESO S71, Montezuma Slough at Roaring River, above salinity control gate
27	SLRAR000	DWR	597652 4216520	38-05-35 121-53-11	DWR-ESO S72, Roaring River at Montezuma Slough, above salinity control gate
28	SLSUS012	CDEC	583595 4226073	38-10-50 122-02-44	CDEC VOL, DWR-ESO S42, Suisun Slough at Volanti Slough
29	SLSUS012	DWR	583595 4226073	38-10-50 122-02-44	CDEC VOL, DWR-ESO S42, Suisun Slough at Volanti Slough

FIGURE II-4

IEP STAGE STATIONS IN THE WEST DELTA

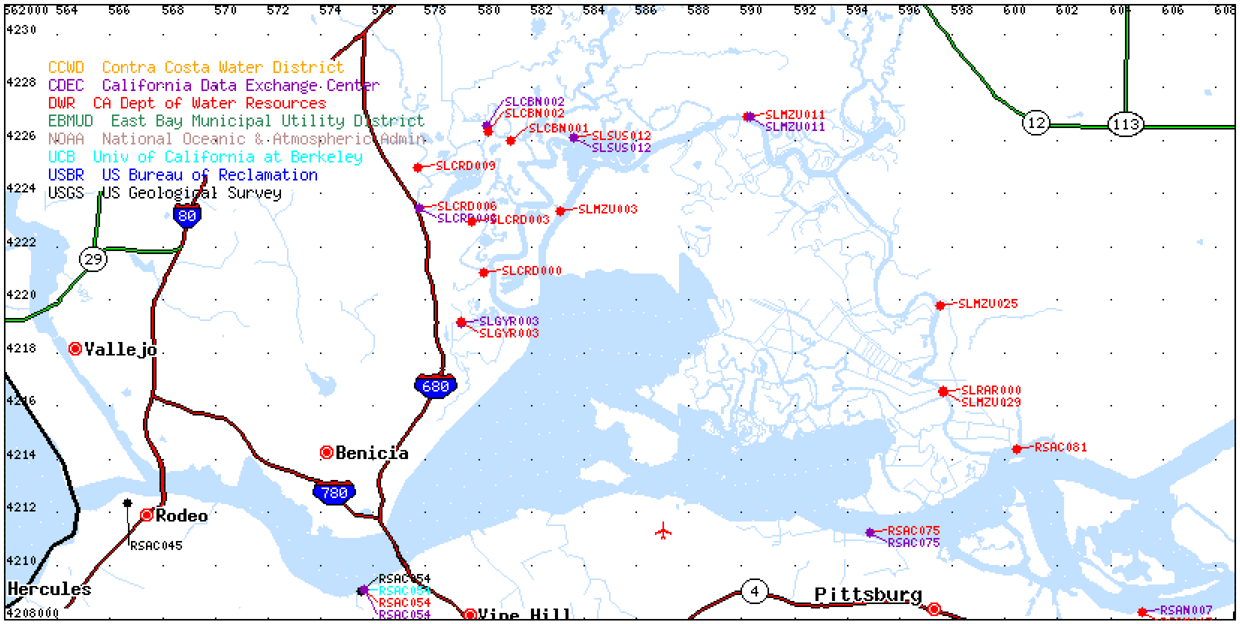


TABLE II-4

IEP FLOW STATIONS IN THE NORTH DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	BYOLO040	DWR	618037 4281687	38-40-40 121-38-35	USGS 11453000, Yolo Bypass near Woodland
2	BYOLO040	USGS	618037 4281687	38-40-40 121-38-35	USGS 11453000, Yolo Bypass near Woodland
3	IEP000	DWR	633594 4269167	38-33-46 121-28-00	IEP Headquarter, DWR-ESO
4	RCSM075	CDEC	671530 4262930	38-50-00 121-03-30	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
5	RCSM075	DWR	670556 4262930	38-30-01 121-02-39	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
6	RCSM075	USGS	670556 4262930	38-30-01 121-02-39	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
7	RMKL070	CDEC	648763 4224819	38-15-90 121-30-20	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
8	RMKL070	DWR	648723 4224775	38-30-01 121-02-39	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
9	RMKL070	EBMUD	648763 4224819		CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
10	RMKL070	USGS	648723 4224569	38-98-31 121-18-09	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
11	RSAC101	CDEC	613909 4223050	38-15-00 121-70-00	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
12	RSAC101	DWR	613906 4224086	38-09-33 121-41-06	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
13	RSAC101	USBR	615184 4224147	38-09-35 121-41-07	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
14	RSAC101	USGS	615209 4224086	38-09-33 121-41-06	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
15	RSAC123	DWR	629888 4233218	38-14-22 121-30-57	DWR-CD 1650, USGS 447905, Sacramento River S of Georgiana Slough
16	RSAC123	USGS	629378 4233148	38-14-20 121-31-18	DWR-CD 1650, USGS 447905, Sacramento River S of Georgiana Slough
17	RSAC128	DWR	629734 4235249	38-15-28 121-31-02	USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel
18	RSAC128	USBR	629734 4235249	38-15-28 121-31-02	USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel
19	RSAC128	USGS	629734 4235250	38-15-28 121-31-02	USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel
20	RSAC155	CDEC	630894 4256604	38-45-00 121-50-00	CDEC FPT, USGS 11447650, Sacramento River at Freeport
21	RSAC155	DWR	630714 4257218	38-27-20 121-30-07	CDEC FPT, USGS 11447650, Sacramento River at Freeport
22	RSAC155	USGS	630714 4257218	38-27-20 121-30-07	CDEC FPT, USGS 11447650, Sacramento River at Freeport
23	RSAC182	DWR	625893 4273944	38-36-25 121-33-15	DWR-CD 2903, Sacramento Weir Spill to Yolo Bypass
24	RSAC240	DWR	617246 4291048	38-45-44 121-39-02	DWR-CD 2930, Sacramento River at Fremont Weir Spill, east of Yolo Bypass

TABLE II-5

IEP STAGE STATION IN THE NORTH DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	CHSAC030	DWR	623240 4259258	38-28-30 121-35-14	DWR-CD 1560, Yolo Bypass near Libson
2	CHSAC031	CDEC	623594 4260151	38-48-30 121.58-30	CDEC LIS, Yolo Bypass near Libson
3	IEP000	DWR	633594 4269167	38-33-46 121-28-00	IEP Headquarter, DWR-ESO
4	RCSM025	DWR	644798 4246636	38-21-29 121-20-34	DWR-CD 1125, Consumnes River at McConnell
5	RCSM075	CDEC	671530 4262930	38-50-00 121-03-30	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
6	RCSM075	DWR	670556 4262930	38-30-01 121-02-39	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
7	RCSM075	USGS	670556 4262930	38-30-01 121-02-39	CDEC MHB, USGS 11335000, Consumnes River at Michigan Bar
8	RMKL005	DWR	624507 4220986	38-07-48 121-34-46	DWR-CD 4100, Mokelumne River (North Fork) at Georgiana Slough
9	RMKL027	CDEC	636582 4235165	38-25-60 121-43-90	CDEC BEN, Mokelumne River (North Fork) at Thorton (near Interstate 5)
10	RMKL032	DWR	637800 4232800		DWR-CD 4175, Mokelumne River (North Fork) near Thornton
11	RMKL070	CDEC	648763 4224819	38-15-90 121-30-20	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
12	RMKL070	DWR	648723 4224775	38-30-01 121-02-39	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
13	RMKL070	EBMUD	648763 4224819		CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
14	RMKL070	USGS	648723 4224569	38-98-31 121-18-09	CDEC WBR, EBMUD station, USGS 11325500, Mokelumne River (North Fork) at Woodbridge
15	RSAC101	CDEC	613909 4223050	38-15-00 121-70-00	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
16	RSAC101	DWR	613906 4224086	38-09-33 121-41-06	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
17	RSAC101	USBR	615184 4224147	38-09-35 121-41-07	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
18	RSAC101	USGS	615209 4224086	38-09-33 121-41-06	CDEC RIV/RVS, DWR-CD 1212, DWR-ESO station, USBR RIV, USGS 455400, Sacramento River at Rio Vista Bridge
19	RSAC123	DWR	629888 4233218	38-14-22 121-30-57	DWR-CD 1650, USGS 447905, Sacramento River S of Georgiana Slough
20	RSAC123	USGS	629378 4233148	38-14-20 121-31-18	DWR-CD 1650, USGS 447905, Sacramento River S of Georgiana Slough
21	RSAC128	DWR	629734 4235249	38-15-28 121-31-02	USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel
22	RSAC128	USBR	629734 4235249		USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel

TABLE II-5. (CONTINUED)

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
23	RSAC128	USGS	629734 4235250	38-15-28 121-31-02	USBR-CVO station, USGS 447890, Sacramento River N of Delta Cross Channel
24	RSAC140	DWR	628258 4245524	38-21-02 121-31-56	DWR-CD 1750, Sacramento River at Snodgrass Slough
25	RSAC155	CDEC	630894 4256604	38-45-00 121-50-00	CDEC FPT, USGS 11447650, Sacramento River at Freeport
26	RSAC155	DWR	630714 4257218	38-27-20 121-30-07	CDEC FPT, USGS 11447650, Sacramento River at Freeport
27	RSAC155	USGS	630714 4257218	38-27-20 121-30-07	CDEC FPT, USGS 11447650, Sacramento River at Freeport
28	RSAC244	DWR	615875 4290719	38-45-34 121-39-59	DWR-CD 2170, Sacramento River at Fremont Weir Spill, west of Yolo Bypass
29	RSMKL024	DWR	632173 4231744	38-13-33 121-29-24	DWR-CD 4150, South Fork of Mokelumne River (South Fork) at New Hope Bridge

FIGURE II-5

IEP FLOW STATIONS IN THE NORTH DELTA

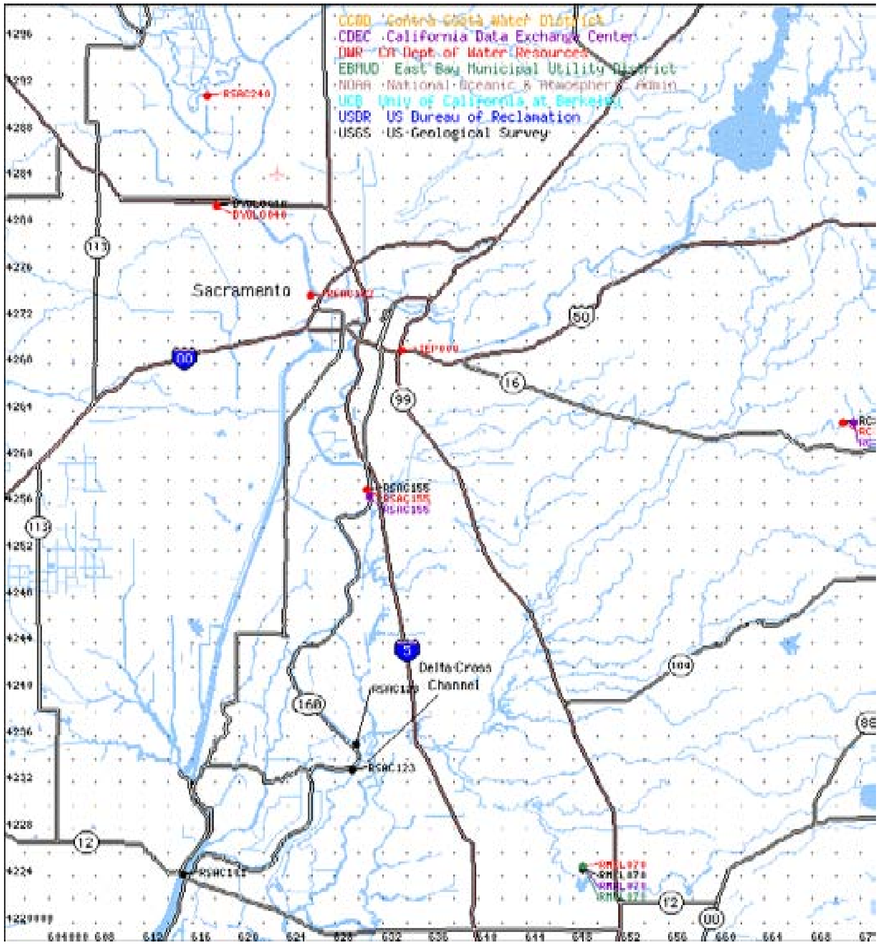


FIGURE II-6

IEP STAGE STATIONS IN THE NORTH DELTA

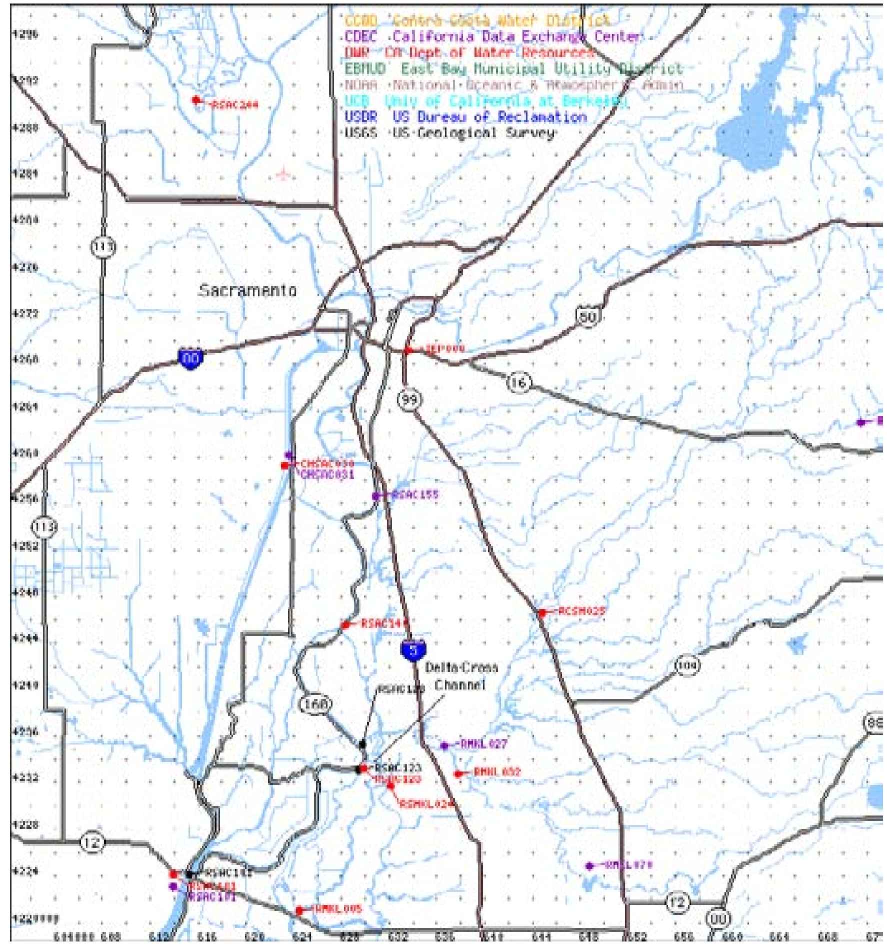


TABLE II-6

IEP FLOW STATIONS IN THE SOUTH DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	CFTRN000	USGS	635719 4205781	37-59-29 121-27-16	USGS TURNER, Turner Cut
2	CHGRL009	DWR	636547 4186803	37-49-13 121-26-55	DWR-CD 5300, USGS 313245, Grant Line Canal at Tracy Blvd Bridge
3	CHGRL009	USGS	637012 4186780	37-49-12 121-26-36	DWR-CD 5300, USGS 313245, Grant Line Canal at Tracy Blvd Bridge
4	CHSWP003	CDEC	621000 4184500		CDEC HRO, DWR-OM-DFD station, State Water Project California Aqueduct at Harvey O. Banks Delta Pumping Plant
5	CHSWP003	DWR	621000 4184500		CDEC HRO, DWR-OM-DFD station, State Water Project California Aqueduct at Harvey O. Banks Delta Pumping Plant
6	CHVCT000	USGS	629368 4192329	37-52-16 121-31-45	USGS VICT-C, Victoria Canal
7	DOM	USGS	608500 4212500		USGS Delta Outflow Monitoring, averaged of stations around
8	LSHL001	USGS	605358 4212207	38-03-12 121-47-57	USGS SHERLN, Sacramento River at Sherman Lake
9	LSHL003	USGS	606615 4209326	38-01-38 121-47-07	USGS ADCP study, San Joaquin River at Mayberry Cut
10	NDOI	CDEC	608500 4213000		CDEC Delta Outflow Index, averaged of stations around
11	RCAL009	DWR	649300 4205400		DWR DSM2
12	RMID005	USGS	630797 4206903	38-00-08 121-30-37	USGS MIDCOL, Middle River south of Columbia Cut
13	RMID015	DWR	628901 4200275	37-56-34 121-31-59	DWR-CD 5468, USGS 312676, Middle River at Middle River
14	RMID015	USGS	628901 4200275	37-56-34 121-31-59	DWR-CD 5468, USGS 312676, Middle River at Middle River
15	ROLD024	CDEC	625516 4203466	37-97-20 121-57-10	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
16	ROLD024	DWR	625507 4203460	37-58-19 121-34-16	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
17	ROLD024	USGS	625510 4203244	37-58-12 121-34-16	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
18	ROLD040	DWR	627559 4187645	37-49-45 121-33-02	DWR-CD 5340, USGS 312970, Old River at Clifton Court Ferry
19	ROLD040	USGS	627538 4187368	37-49-36 121-33-03	DWR-CD 5340, USGS 312970, Old River at Clifton Court Ferry
20	ROLD047	DWR	628324 4185592	37-48-38 121-32-32	USGS OLDDMC, DWR-CD 5366, Old River near Delta Mendota Canal (SE of barrier)
21	ROLD047	USGS	628448 4185501	37-48-35 121-32-27	USGS OLDDMC, DWR-CD 5366, Old River near Delta Mendota Canal (SE of barrier)
22	RSAN018	USBR	615060 4212215	38-03-08 121-41-19	USBR JER, USGS 337190, San Joaquin River at Jersey Point
23	RSAN018	USGS	614866 4212182	38-03-07 121-41-27	USBR JER, USGS 337190, San Joaquin River at Jersey Point
24	RSAN046	USGS	634413 4209521	38-01-31 121-28-07	USGS SJR-TC, San Joaquin River between Turner Cut and Columbia Cut
25	RSAN063	USGS	646807 4199806	37-56-09 121-19-46	USGS 304810, San Joaquin River at Stockton
26	RSAN112	CDEC	652848 4170077	37-66-70 121-26-70	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
27	RSAN112	DWR	653079 4171092	37-40-34 121-15-51	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
28	RSAN112	USBR	652933 4171059	37-40-33 121-15-57	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
29	RSAN112	USGS	653079 4171092	37-40-34 121-15-51	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
30	SLDUT007	USGS	617023 4207958	38-00-49 121-40-01	USGS 313433, Dutch Slough at Jersey Island

TABLE II-6 (CONTINUED)

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
31	SLMAY002	USGS	607555 4210109	38-02-03 121-46-28	USGS MAY-SL, Mayberry Slough
32	SLTRM004	DWR	615298 4216072	38-05-13 121-41-07	DWR-CD 5060, USGS 337080, Three Mile Slough at San Joaquin River
33	SLTRM004	USGS	615273 4216133	38-05-15 121-41-08	DWR-CD 5060, USGS 337080, Three Mile Slough at San Joaquin River

TABLE II-7

IEP STAGE STATIONS IN THE SOUTH DELTA

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
1	CHGRL009	DWR	636547 4186803	37-49-13 121-26-55	DWR-CD 5300, USGS 313245, Grantline Canal at Tracy Blvd Bridge
2	CHGRL009	USGS	637012 4186780	37-49-12 121-26-36	DWR-CD 5300, USGS 313245, Grantline Canal at Tracy Blvd Bridge
3	CHGRL012	DWR	639963 4186810	37-49-13 121-26-38	DWR-CD 5310, Grantline Canal at Head
4	CHWST000	DWR	626900 4188315		DWR-OM Clifton Court Forebay Radial Gates
5	RMID007	DWR	629700 4206855	38-00-07 121-31-22	DWR-CD 5460, Middle River at Bacon Island
6	RMID015	DWR	628901 4200275	37-56-34 121-31-59	DWR-CD 5468, USGS 312676, Middle River at Middle River
7	RMID015	USGS	628901 4200275	37-56-34 121-31-59	DWR-CD 5468, USGS 312676, Middle River at Middle River
8	RMID023	DWR	632875 4194605	37-53-28 121-29-20	USBR VIC, DWR-CD 5500, Middle River at Borden Highway
9	RMID023	USBR	632923 4194605	37-53-28 121-29-18	USBR VIC, DWR-CD 5500, Middle River at Borden Highway
10	RMID027	DWR	635824 4193574	37-52-53 121-27-20	DWR-CD 5503, Middle River at Tracy Blvd
11	RMID040	DWR	643024 4188486	37-50-04 121-22-29	DWR-CD 5540, Middle River at Mowry Bridge, 1.7 km N of Old River
12	ROLD024	CDEC	625516 4203466	37-97-20 121-57-10	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
13	ROLD024	DWR	625507 4203460	37-58-19 121-34-16	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
14	ROLD024	USGS	625510 4203244	37-58-12 121-34-16	CDEC BAC, DWR-CD 5250, USGS 313405, Old River at Bacon Island
15	ROLD034	CCWD	625871 4194731		DWR-CD 5270, CCWD pumping station, Old River near Byron
16	ROLD034	DWR	625871 4194731	37-53-28 121-34-09	DWR-CD 5270, CCWD pumping station, Old River near Byron
17	ROLD040	DWR	627559 4187645	37-49-45 121-33-02	DWR-CD 5340, USGS 312970, Old River at Clifton Court Ferry
18	ROLD040	USGS	627538 4187368	37-49-36 121-33-03	DWR-CD 5340, USGS 312970, Old River at Clifton Court Ferry
19	ROLD046	DWR	628028 4185772	37-48-44 121-32-44	DWR-CD 5365, Old River near Delta Mendota Canal (NW of barrier)
20	ROLD047	DWR	628324 4185592	37-48-38 121-32-32	USGS OLDDMC, DWR-CD 5366, Old River near Delta Mendota Canal (SE of barrier)

TABLE II-7 (CONTINUED)

	Station	Agency	UTM E & N (zone 10S, NAD83)	Latitude Longitude (N W)	Location Info
21	ROLD047	USGS	628448 4185501	37-48-35 121-32-27	USGS OLDDMC, DWR-CD 5366, Old River near Delta Mendota Canal (SE of barrier)
22	ROLD059	CDEC	636575 4185107	37-80-50 121-44-90	CDEC OLR, DWR-CD 5380, Old River at Tracy Blvd
23	ROLD059	DWR	636575 4185108	37-48-18 121-26-55	CDEC OLR, DWR-CD 5380, Old River at Tracy Blvd
24	ROLD074	DWR	647111 4185567	37-48-27 121-19-44	DWR-CD 5400, Old River at Head
25	RSAN007	CDEC	605190 4208259	38-01-04 121-48-06	CDEC ANH, DWR-CD 5020, San Joaquin River at Antioch between lights 7 & 8
26	RSAN007	DWR	605190 4208259	38-01-04 121-48-06	CDEC ANH, DWR-CD 5020, San Joaquin River at Antioch between lights 7 & 8
27	RSAN018	USBR	615060 4212215	38-03-08 121-41-19	USBR JER, USGS 337190, San Joaquin River at Jersey Point
28	RSAN018	USGS	614866 4212182	38-03-07 121-41-27	USBR JER, USGS 337190, San Joaquin River at Jersey Point
29	RSAN032	DWR	623573 4218012	38-06-12 121-35-26	USBR SAL, DWR-CD 5100, San Joaquin River at San Andreas Landing
30	RSAN032	USBR	623553 4218043	38-06-13 121-35-27	USBR SAL, DWR-CD 5100, San Joaquin River at San Andreas Landing
31	RSAN043	CDEC	631964 4212224	38-05-00 121-49-60	CDEC VNI&VNE, DWR-CD 5580, San Joaquin River at Venice Island
32	RSAN043	DWR	631979 4212256	38-03-01 121-29-45	CDEC VNI&VNE, DWR-CD 5580, San Joaquin River at Venice Island
33	RSAN052	DWR	638879 4206512	37-59-51 121-25-06	DWR-CD 5620, San Joaquin at Rindge Pump
34	RSAN058	DWR	643630 4202740	37-57-46 121-21-54	DWR-CD 5660, Stockton Ship Channel at Burns Cutoff
35	RSAN063	USGS	646807 4199806	37-56-09 121-19-46	USGS 304810, San Joaquin River at Stockton
36	RSAN072	DWR	647632 4191928	37-51-53 121-19-18	DWR-CD 5740, San Joaquin River at Brandt Bridge
37	RSAN112	CDEC	652848 4170077	37-66-70 121-26-70	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
38	RSAN112	DWR	653079 4171092	37-40-34 121-15-51	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
39	RSAN112	USBR	652933 4171059	37-40-33 121-15-57	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
40	RSAN112	USGS	653079 4171092	37-40-34 121-15-51	CDEC VER/VNS, USBR VER, USGS 11303500, San Joaquin River at Vernalis
41	SLDUT007	USGS	617023 4207958	38-00-49 121-40-01	USGS 313433, Dutch Slough at Jersey Island
42	SLFRC005	DWR	654074 4193865	121-14-53 37-52-52	DWR-CD 2805, French Camp Slough near French Camp
43	SLRCK005	DWR	619595 4203864	37-58-35 121-38-18	DWR-CD 5220, Rock Slough at Contra Costa Canal intake
44	SLTMP000	DWR	639366 4183521	37-47-25 121-25-02	DWR-CD 5420&5421, Tom Paine Slough above Intake Structure
45	SLTMP017	DWR	645331 4181065	37-46-02 121-21-00	DWR-CD 5425, Tom Paine Slough at Pescadero Pumping Plant # 6
46	SLTRM004	DWR	615298 4216072	38-05-13 121-41-07	DWR-CD 5060, USGS 337080, Three Mile Slough at San Joaquin River
47	SLTRM004	USGS	615273 4216133	38-05-15 121-41-08	DWR-CD 5060, USGS 337080, Three Mile Slough at San Joaquin River

FIGURE II-7

IEP FLOW STATIONS IN THE SOUTH DELTA

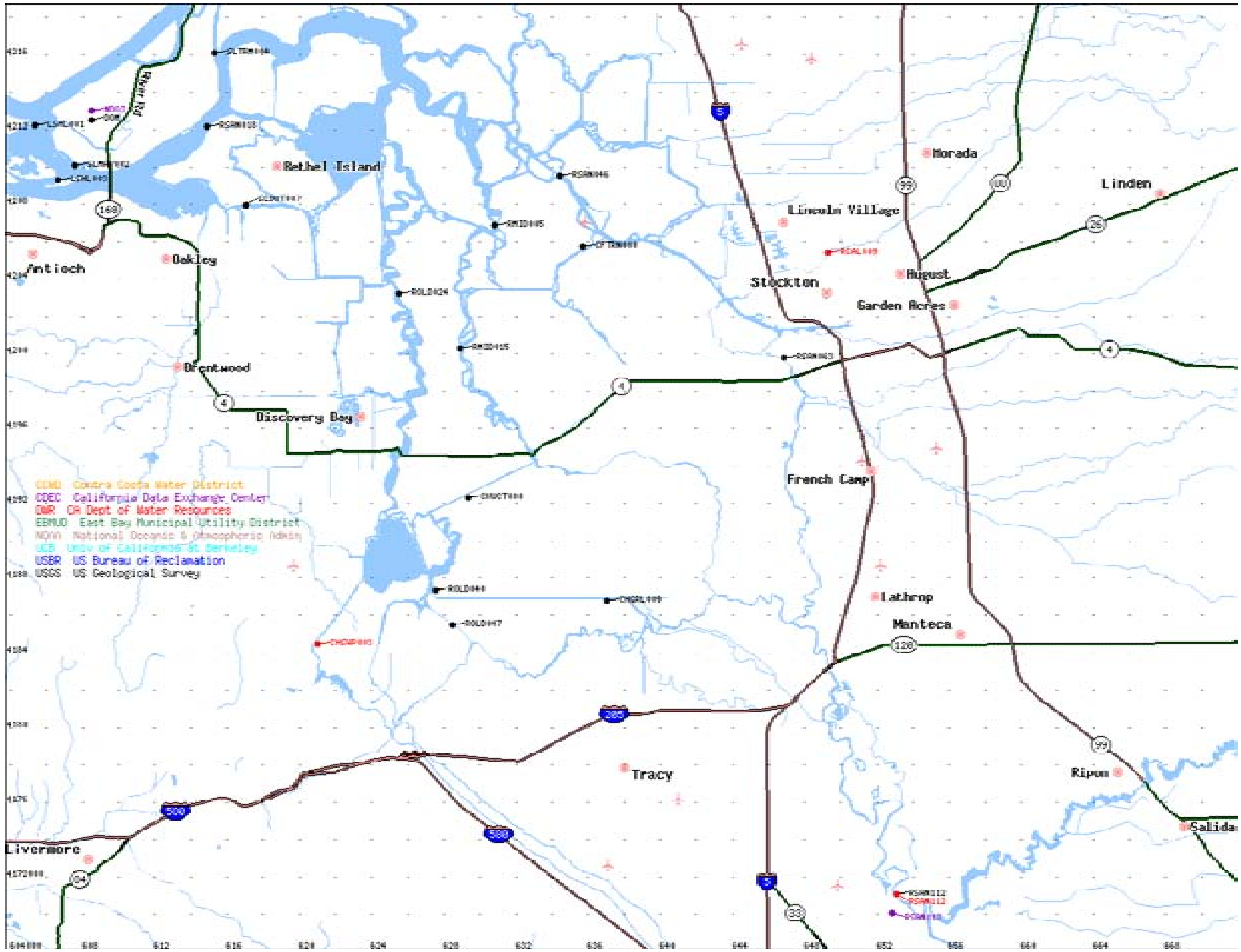


FIGURE II-8

IEP STAGE STATIONS IN THE SOUTH DELTA

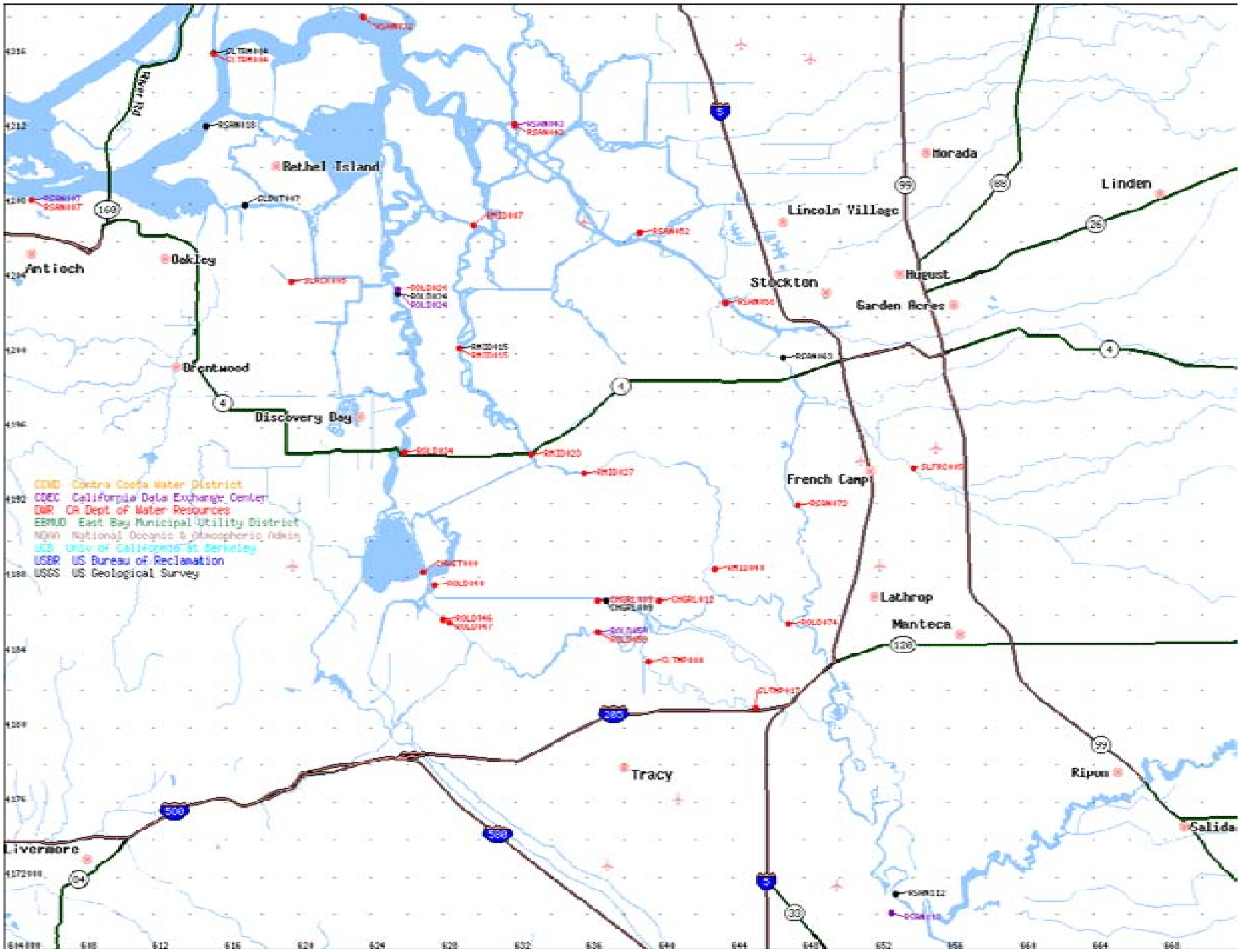
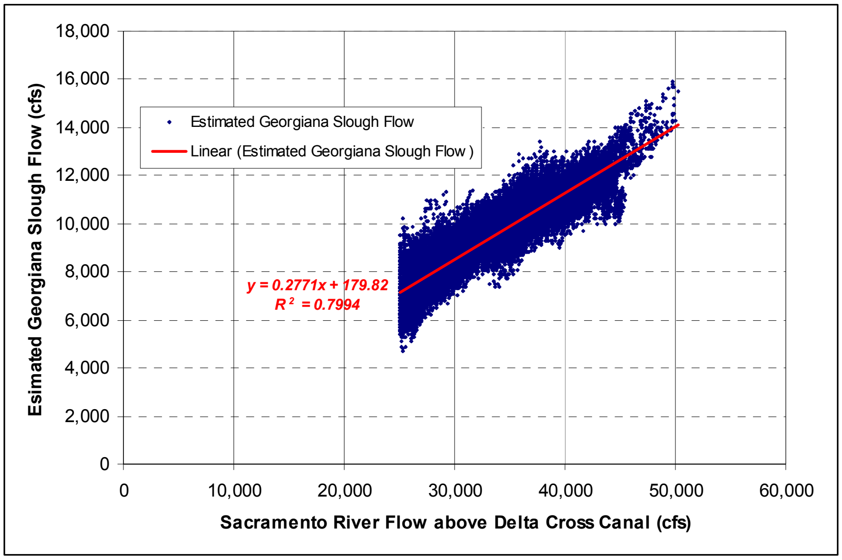


FIGURE II-9

FLOW SPLIT RELATIONSHIP BETWEEN SACRAMENTO RIVER AND GEORGIANA SLOUGH

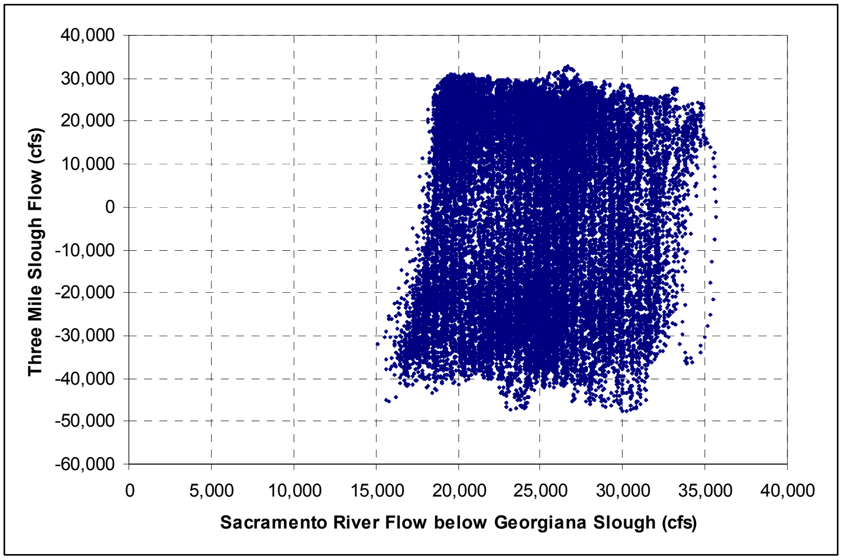


Sacramento River Flow Split into the Three Mile Slough near Sherman Island

The Sacramento River flow downstream from the Georgiana Slough further splits into the Three Mile Slough near Sherman Island. Figure II-10 shows the scatter plot of flows in the Sacramento River and the Three Mile Slough when the Sacramento River flow above the Delta Cross Channel exceeds 25,000 cfs (i.e., the Delta Cross Channel Gates is closed). The similar ranges of Three Mile Slough flow with respect to any Sacramento River flow suggests no relationship between these two flows. It is evident that the flow in the Three Mile Slough is strongly influenced by tides since the reverse flows are common and significant.

FIGURE II-10

FLOW SPLIT RELATIONSHIP BETWEEN SACRAMENTO RIVER AND THREE MILE SLOUGH



Flow Splits of San Joaquin River

The records of San Joaquin River are generally not supportive to the analysis of flow splits. The major splits of San Joaquin River flow in the Delta are as follows.

- Flow splits between the San Joaquin River and the Paradise Cut at the Paradise Dam
- Flow splits between the San Joaquin River and the Old River near Lathrop; and
- Flow splits between the Old River and the Middle River at Union Island.

Long-term flow measurements of the San Joaquin River and its distributaries are available at Old River at Bacon Island (ROLD024), Middle River at Middle River (RMID015), San Joaquin River at Stockton (RSAN063), and San Joaquin River at Vernalis (RSAN112). (See Figure II-5 for locations.) The length of records at these stations is more than 10 years, except for the San Joaquin River at Stockton (RSAN063). These stations are located too far away from each other to be sufficient in the determination of flow splits at any of the three bifurcation locations previously described.

Some short-term measurements (about or less than 1 year) are available at Grant Line Canal at Tracy Boulevard (CHGRL009), Victoria Canal (CHVCT000), Old River at Clifton Court Ferry (ROLD040), and Old River near Delta Mendota Canal, SE of Barrier (ROLD047). However, due to their locations and short duration of records, these stations provide little information for flow splits.

Flow-Stage Relationship in Delta Waterways

The flow-stage relationship in Delta waterways is not straightforward due to the prominent tidal influence. Figures II-11 through II-12 show the flow and stage at selective locations in the Delta during January 1 through 10, 1997. In the central Delta (Figures II-12 for Jersey Point and II-13 for Middle River below Victoria Canal), the flow and stage do not correlate well. Rather, daily fluctuations of flows and stages are not in synchronicity, and the peak flow occurred several days apart from the peak stage. It is evident that the stages at Jersey Point and are more influenced by tides than by the San Joaquin River flow.

The tidal influence is less observed in Figure II-11 for the Sacramento River above the Delta Cross Channel (RSAC128). Flow and stage are showing stronger correlation; however, it is evident that the similar stages in January 1 and January 10 correspond to flows with about 4,000 cfs in difference. At Vernalis (Figure II-14), the San Joaquin River is clearly outside of the tidal influence zone because no daily fluctuation in flow and stage are observed. Thus, the definition of a flow-stage relationship of the San Joaquin River at Vernalis is more feasible. (Note that possible errors in the records at Vernalis were reported. See Chapter III for details.)

The above comparisons indicate that the flow and stage (and thus the hydrodynamics) in Delta waterways are not straightforward, and are results of hydraulic balance among tide currents, Delta inflows, and other operational and hydrological conditions occurring simultaneously in the Delta. All of these contributing factors need to be considered simultaneously when discussing the existing hydrodynamic conditions in the Delta.

FIGURE II-11

SACRAMENTO RIVER FLOW AND STAGE ABOVE THE DELTA CROSS CHANNEL (RSAC128) FROM JANUARY 1 THROUGH 10, 1997

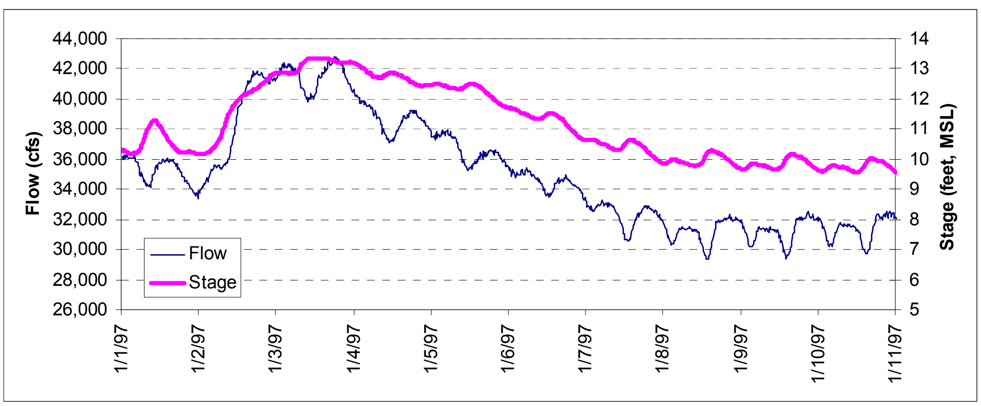


FIGURE II-12

SAN JOAQUIN RIVER FLOW AND STAGE AT JERSEY POINT (RSAN018) FROM JANUARY 1 THROUGH 10, 1997

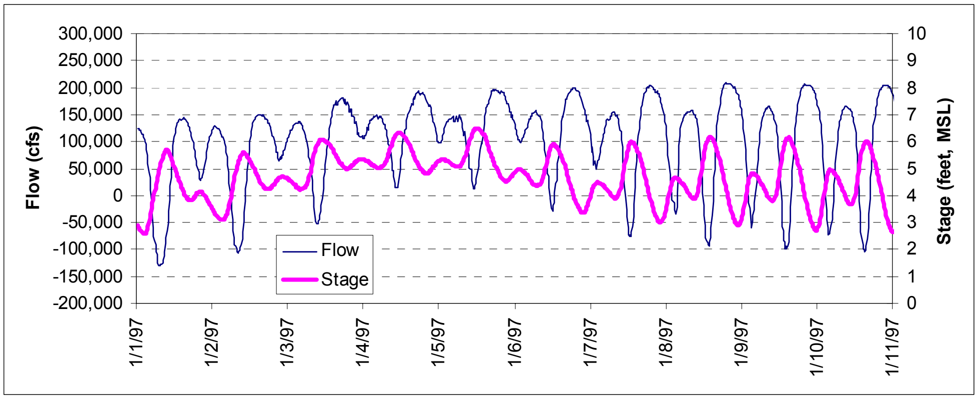


FIGURE II-13

MIDDLE RIVER FLOW AND STAGE AT MIDDLE RIVER BELOW VICTORIA CANAL (RMID015) FROM JANUARY 1 THROUGH 10, 1997

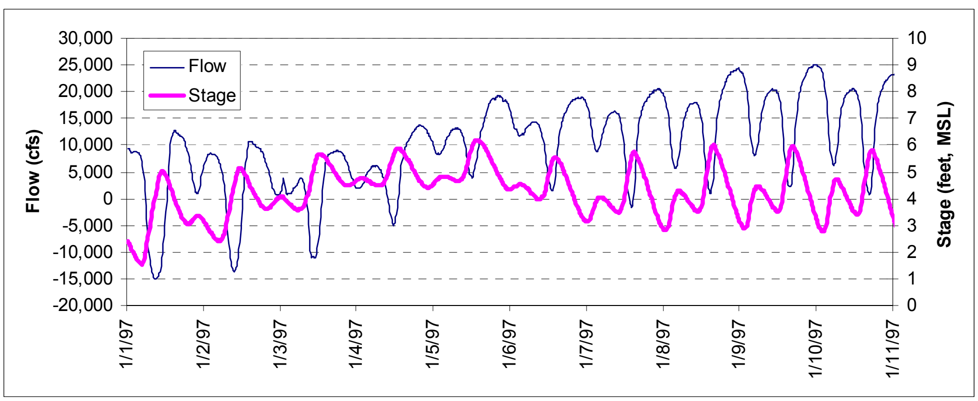
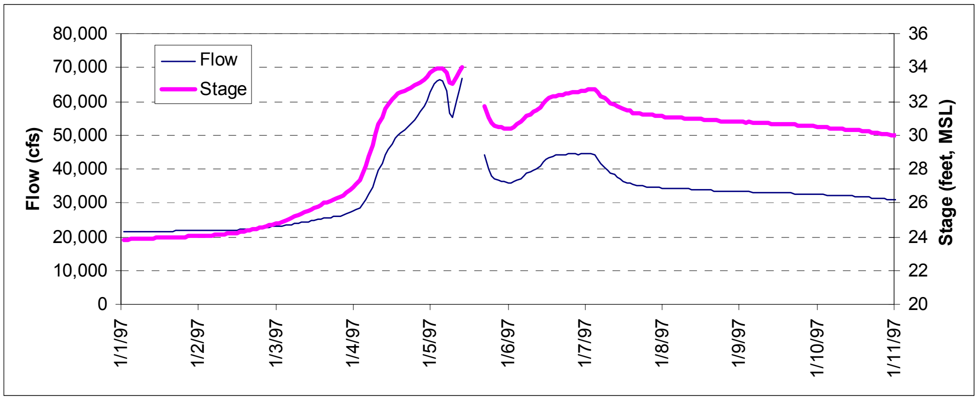


FIGURE II-14

SAN JOAQUIN RIVER FLOW AND STAGE AT VERNALIS (RSAN112) FROM JANUARY 1 THROUGH 10, 1997



CHAPTER III

DELTA HYDRODYNAMICS DURING 1997 FLOOD

HIGHLIGHTS OF 1997 FLOOD

System-wide Conditions

The 1997 Flood was caused by one of the largest storms in Northern California in the century. The storm represents a classic orographic event with warm winds from the southwest blowing over the Sierra Nevada and dropping astounding amounts of rain at the middle and high elevations. Watersheds were already saturated from earlier storms. The volume of runoff exceeded previously recorded volumes in most of the Sierra streams flowing to the west. Many of the flood control reservoirs receiving these historical volumes filled and made record downstream releases.

The Sacramento River basin flood control reservoirs stored the storm runoff and releases were made within downstream channel capacities. Maximum federal flood control storage seasonally reserved in the Sacramento River system totals nearly 2.8 million acre-feet in the six largest flood control projects (Shasta, Oroville, Black Butte, New Bullards Bar, Indian Valley, and Folsom Dams). In the San Joaquin River basin all but two flood control reservoirs controlled the runoff to within the capacity of each of their respective downstream channels. The releases from Friant Dam and Don Pedro Dam greatly exceeded their respective downs stream channel capacity. Releases from New Exchequer Dam on the Merced River also exceeded downstream design flows, but the outflows were contained within the levee system. Maximum federal flood control storage in the San Joaquin River system totals nearly 2.4 million acre-feet in seventeen lakes and reservoirs (Camanche, New Hogan, Farmington, New Melones, Don Pedro, New Exchequer, Los Banos, Burns, Bear, Owens, Mariposa, Buchanan, Hidden, Friant, Big Dry Creek, and Pine Flat Dams).

Many levee breaks and regional flooding occurred in the Central Valley due to the record high flows. Damages are reported from areas along the main rivers and their tributaries, and the major damage areas are within Yuba, Stanislaus, and San Joaquin Counties. Detailed hydrologic conditions and damages in the Central Valley during the 1997 flood can be found in *The Hydrology of the 1997 New Year's Flood, Sacramento and San Joaquin River Basins* (DWR, 1999), *Post-Flood Assessment* (Comprehensive Study, 1999), and *The Final Report of the Governor's Flood Emergency Action Team* (FEAT, 1997).

Delta Inflows

The Delta receives water from the Sacramento River (including the Yolo Bypass), the San Joaquin River, and the eastside streams. The peak daily flows and the corresponding return frequency of major Delta tributaries are shown in Tables III-1 and III-2, respectively. Peak flows exceeded previous maximums were recorded at gages including Tuolumne River at Modesto, Consumnes River at Michigan Bar, South Fork American River near Placerville and South Fork Mokelumne River near West Point. Except for the South Fork American River flow, these record high flows entered the Delta with little to no further regulation.

TABLE III-1

MAXIMUM DAILY FLOWS OF MAJOR TRIBUTARIES TO THE DELTA

Tributary	Channel Design Capacity (cfs)	Maximum Daily Flow (cfs)	Date
Sacramento River (Freeport)	110,000	113,000	January 3
Yolo Bypass	480,000	438,000	January 3
San Joaquin River (Vernalis)	52,000	54,300	January 5
Consumnes River		53,600	January 2
Mokelumne River		5,000	January 2
Source: DWR, *The Hydrology of the 1997 New Year's Flood, Sacramento and San Joaquin River Basins*, December 1999.			

TABLE III-2

ESTIMATED RETURN FREQUENCY OF 1997 FLOOD

AT SELECTIVE LOCATIONS NEAR THE DELTA

Location	Estimated Return Frequency (years)	Note
Sacramento River at the Latitude of Sacramento	90-110	Including Yolo Bypass at Woodland, and the American River
San Joaquin River at Vernalis	80-100	Including out-of-channel flow
Mokelumne River below Camanche Dam*	55-65	
Calaveras River below New Hogan Dam*	5-15	Including Mormon Slough at Bellota
Source: Comprehensive Study, *Post-Flood Assessment*, March 1999.		
*Estimated from unregulated volume-duration flood flow-frequency relationship.		

CVP-SWP Operations

The Delta Cross Channel gates were closed on November 20, 1996 for fishery reasons and were not opened until May 16, 1997. However, the south Delta exports for CVP and SWP were not completely shut down during the 1997 Flood. Figure III-1 shows the south Delta exports for CVP and SWP during December 1996 and January 1997.

During the week of December 12 through 16, the SWRCB approved pumping of CVP water at Banks Pumping Plant to facilitate high exports during a juvenile salmon migration study being conducted by USFWS. SWP storage in the San Luis Reservoir was already slightly above its allocated share and delivery requests were less than 2,000 cfs, making capability available at Banks Pumping Plant. During these five days, 46,324 AF was pumped for the CVP, most of which was used to fill the federal share of storage in San Luis Reservoir. SWP's pumping was suspended on December 10 when the storage of the San Luis Reservoir reached the desired goal of 1.12 million acre-feet.

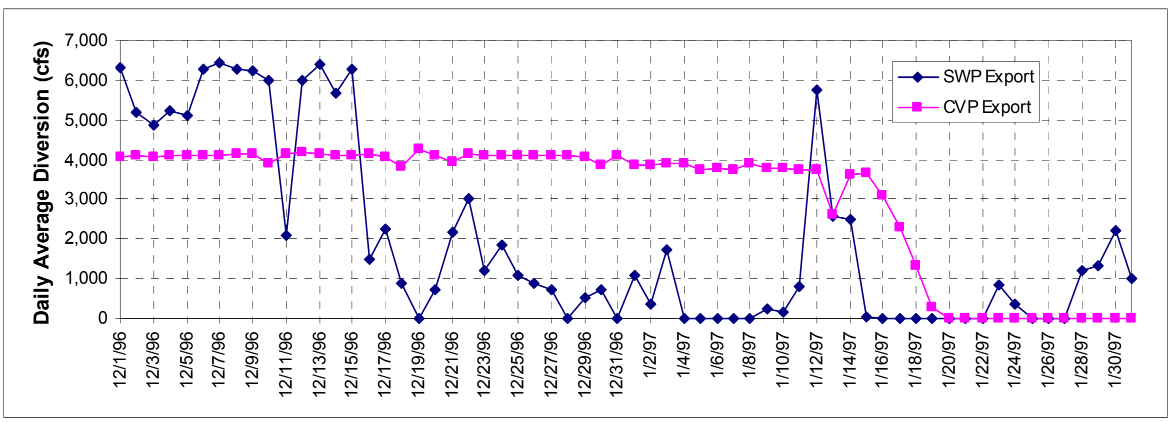
In January, pumping at the Banks pumping plant exceeded inflows of the Clifton Court Forebay at mid-month to relieve south Delta flooding and provide emergency flood control space. This reduced the Forebay water surface to minimum operational elevation and it was not refilled the Forebay until January 22.

The CVP export remained at about 4,000 cfs as in December 1996 before the flood event until late January. The export was then curtailed to zero mainly because the San Luis Reservoir was full. The combined CVP and SWP export during the 1997 Flood did not significantly change the flooding conditions in the Delta although helpful.

FIGURE III-1

SWP AND CVP SOUTH DELTA DAILY AVERAGE EXPORTS

DURING THE 1997 FLOOD



Tidal Ranges

Tidal Ranges in the 1997 Flood

Figure III-2 shows the tidal ranges of the Sacramento River at Martinez. The peak flow of the Sacramento River at Freeport in the 1997 Flood occurred on January 3, and that of the San Joaquin River at Vernalis occurred on January 5 (based on available data). The tidal ranges were enhanced by the parallax effect that occurred around January 2 (see Chapter II). And finally, the third quarter moon occurred around January 2, creating a neap tide (the lunar phase effect). As a result, the 1997 Flood, although significant, was not of its worst scenario in terms of enhancements form astronomical influences due to the earlier arrival time of the Sacramento River flow.

Martinez is in the west portion of the legal Delta; however, river stages at Martinez are not completely controlled by the tides. The water stages during the January 1 through 5 periods appear to be affected by the large Delta inflows, especially those from the Sacramento River basin. They are higher in general compared with those during the next neap tide around January 16.

Comparison to Other Periods

Tidal ranges during three other historical periods were compared to those observed in the 1997 Flood. Figure III-3 shows the tidal ranges in July 1997, which are lower than those in January by as much as one foot during spring tides. As previously mentioned, the tidal ranges are smallest around July 2 when the earth is the farthest from the sun.

Another comparison was made to the tides during the 1995 Flood. In 1995, the largest storm systems hit California January 8-10 and March 5-10. The January storms resulted in more damages in the Sacramento River Basin, whereas the San Joaquin River basin was not as severely affected. The average daily flow in the Sacramento River at Freeport peaked at 95,700 cfs on January 12 and at 91,200 cfs on January 28. No significant flow was observed in the San Joaquin River at Vernalis. The highest daily average flow was 11,500 cfs on January 29. Figure III-4 shows the tidal ranges at Martinez during the 1995 January Flood.

The ranges of the spring tides in late January 1995 is comparable to those observed in the 1997 Flood (also in January). The stages at Martinez appear to be influenced by the large inflows to the Delta, suggested by the affected neap tide patterns in early and late January. Since the inflows from the San Joaquin River were not significant, the impacts were mostly from Sacramento River inflows.

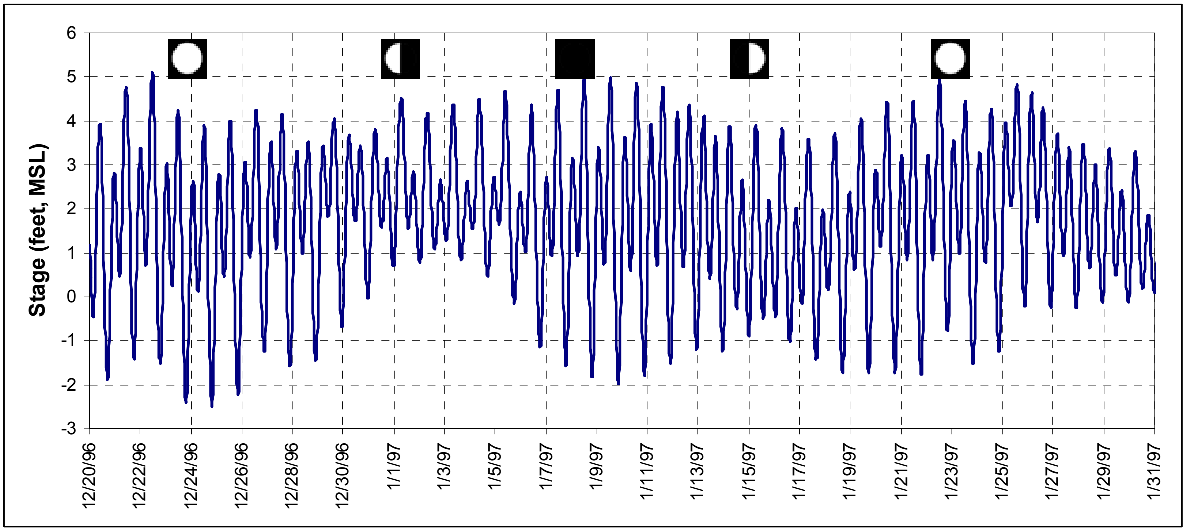
In March 1995, the storms were mostly on the coastal ranges and southern California. The average daily flow in the Sacramento River at Freeport peaked at 99,500 cfs on March 11 and 12. In the San Joaquin River at Vernalis, the highest daily average flow was 25,900 cfs on March 20. Figure III-5 shows the tidal ranges at Martinez in the 1995 March Flood. Again, the stages at Martinez appear to be affected by the large inflows from Sacramento River during the March 8 through 12 period. The next affected period is in late March, coincided when the arrival time of the peak flow from the San Joaquin River.

Comparison with Historical Daily Average Tides

Figure III-6 shows the comparison of the distribution of daily average tidal ranges at Martinez. Three periods are compared in the figure: the entire record length from August 1988 to December 2000, one month period from 12/20/96 though 1/19/97, and one week period from 1/1/97 through 1/7/97. The parallax effect that enhanced the tidal ranges in January is evident in this comparison, as well as the high tide conditions during the peak of 1997 Flood. (Note that the new or full moon closest to the peak of 1997 Flood was around January 9.)

FIGURE III-2

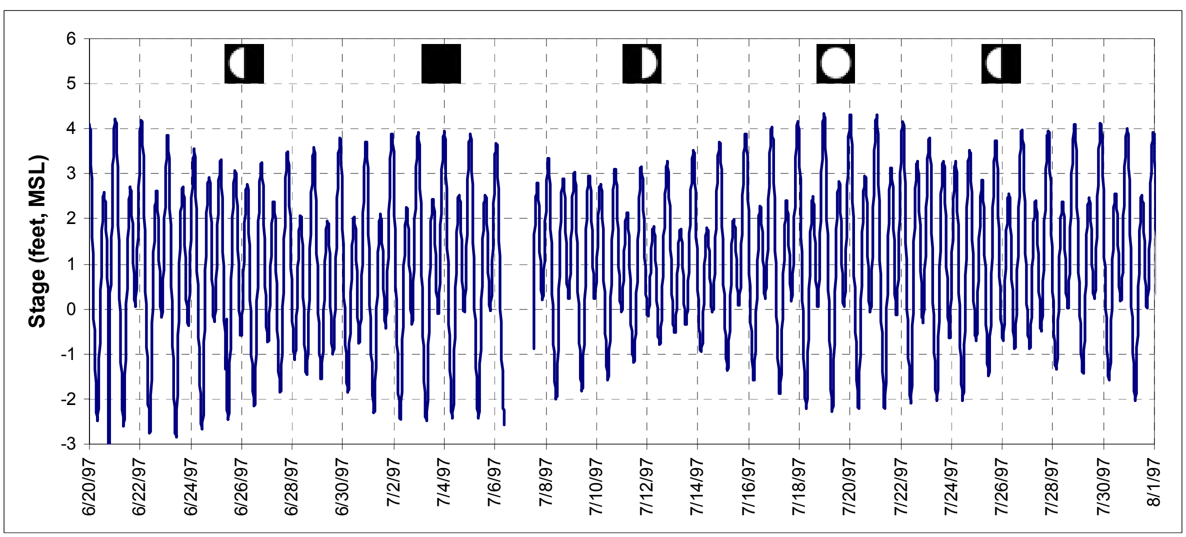
STAGES OF SACRAMENTO RIVER AT MARTINEZ (RSAC054): 12/20/96 THROUGH 1/31/97



* Moon phases are approximate.

FIGURE III-3

STAGES OF SACRAMENTO RIVER AT MARTINEZ (RSAC054): 6/20/97 THROUGH 8/1/97

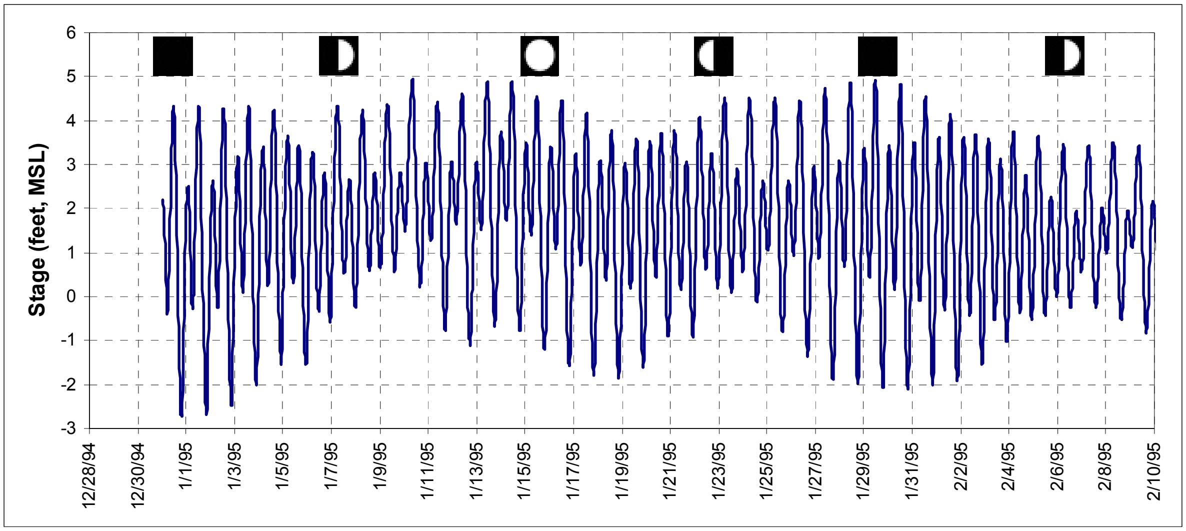


* Moon phases are approximate.

FIGURE III-4

STAGES OF SACRAMENTO RIVER AT MARTINEZ (RSAC054):

12/28/94 THROUGH 2/10/95

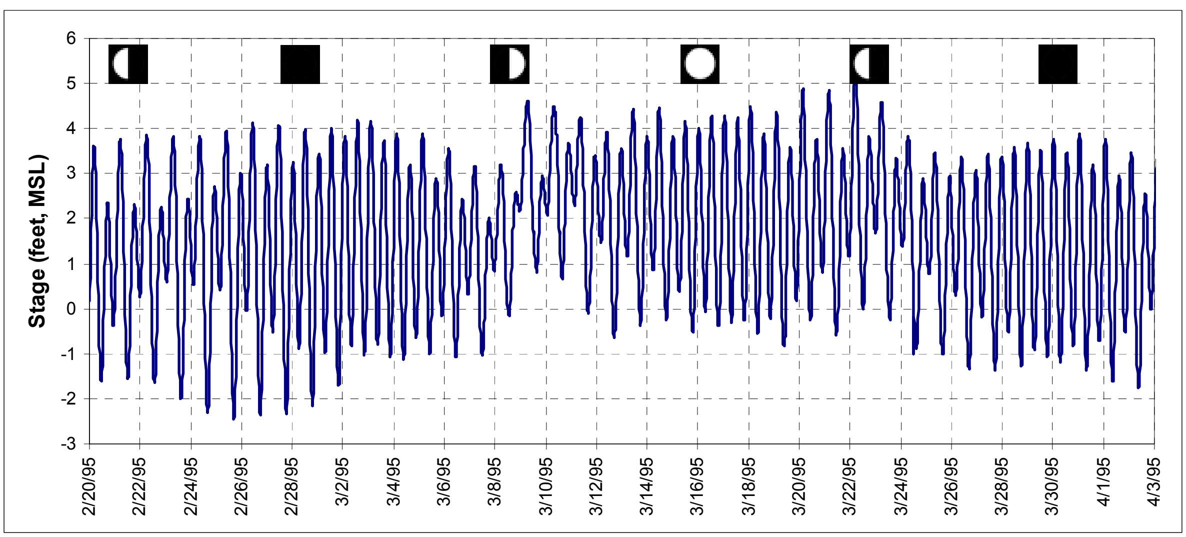


* Moon phases are approximate.

FIGURE III-5

STAGES OF SACRAMENTO RIVER AT MARTINEZ (RSAC054):

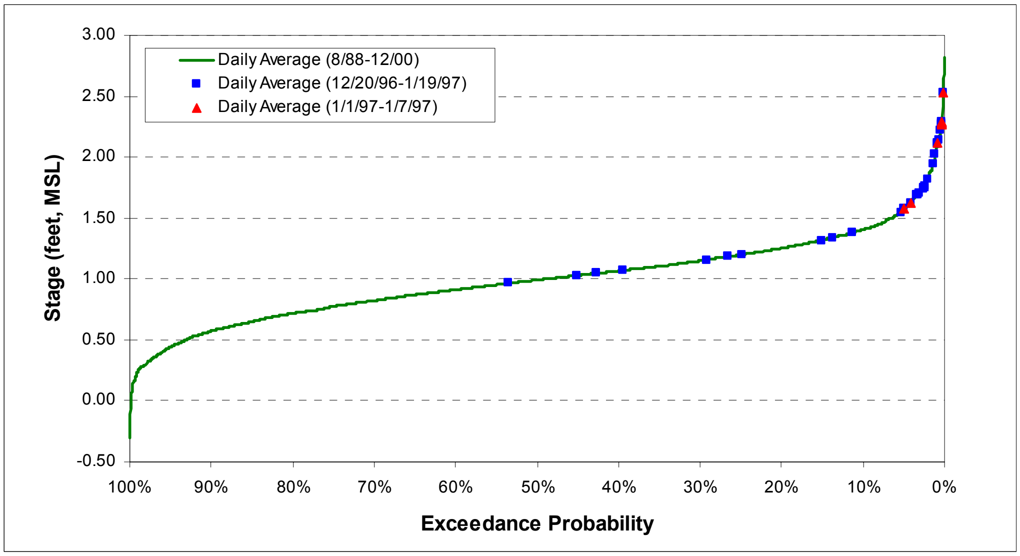
2/20/95 THROUGH 4/3/95



* Moon phases are approximate.

FIGURE III-6

DISTRIBUTION OF DAILY AVERAGE STAGE OF SACRAMENTO RIVER AT MARTINEZ (RSAC054)



Flooding in the Delta

Table III-3 shows the areas in the Delta and its vicinity affected by the 1997 flood. Most levees in the Delta held during the flood. Project levees in the south Delta were damaged or overtopped near the Paradise Cut and the San Joaquin River. No damages were reported for the project levees in the north Delta.

FLOW AND STAGE IN THE DELTA DURING THE 1997 FLOOD

The Delta is a converging point of tides, and river flows from the Sacramento River, the San Joaquin River and eastside tributaries. The river stage at any point in the Delta is a result of hydraulic balance among all the controlling factors.

Figures III-7 through 3-10 show the recorded flow and stages at selected measurement points along the Sacramento River, the San Joaquin River, the Old River and the Middle River from December 1, 1996 to February 28, 1997. During the 1997 flood, many stations, including San Joaquin River at Vernalis, apparently experienced difficulties in recording flow or stage. The tidal effects on river stage are typically shown in a frequency of approximately two cycles per day, and a larger tidal effect is observed roughly twice each month.

TABLE III-3

AREAS IN THE DELTA AND ITS VICINITY AFFECTED BY FLOODING DURING THE 1997 FLOOD

Stream	Area	Description
Consumnes River	Wilton	Four breaks and one overtopping of private levees
Consumnes River	Sacramento and San Joaquin Counties	Numerous breaks and overtopping of private levees.
San Joaquin River/ Stanislaus River	RD 2064 (River Junction)	East levee failed in two places
San Joaquin River	RD 2075 (McMullen Ranch)	East levee failed in three places
San Joaquin River	RD 2094 (Walthall Tract)	East levee breached in four places; water from RD 2094 break flooded RD 2096
San Joaquin River	RD 2096 (Weatherbee Lake)	East levee failed; mouth of Walthall Slough
Paradise Cut	RD 2107 (Mossdale Tract)	East levee break floods RDs 2062 (Stuart Track) and 2107 (Mossdale Track)
Paradise Cut	RD 2095 (Paradise Junction)	Partially inundated when south levee failed
Paradise Cut	RD 2058 (Peecaredo District)	Partially flooded by overflow of unleveed Tom Paine Slough
Prospect Island	Prospect Island	Multiple levee breaks
Source: Comprehensive Study, *Post-Flood Assessment*, 1999.		

Sacramento River

Figure III-7 shows the comparison of Sacramento River stages at various locations with the concurrent flood hydrographs of the Sacramento River at Freeport during the 1997 flood. The San Joaquin River stages at Venice Island are also shown in the figure for comparison.

The river stages of the Sacramento River near the Delta Cross Channel are mainly affected by the flows in the Sacramento River. The tidal influences at these locations are visible but not the major factor. However, as the Sacramento River entering into the Delta, the river stages are more likely affected by the tidal ranges. The impacts from the high flows in the Sacramento River are still prominent and the river stages deviated more from the pattern of tidal ranges observed at Martinez.

It is important to note that the stages of San Joaquin River at Venice Island are consistently lower than those observed in the Sacramento River. There may be a datum shift in the historical data; however, the stages at Venice Island are clearly controlled by the tides and the Sacramento River flows. That is, the high flows in the Sacramento River and the high tides created a hydraulic barrier that controlled the drainage from the San Joaquin River.

San Joaquin River

Figure III-8 shows the comparison of San Joaquin River stages at various locations with the concurrent flood hydrographs of the Sacramento River at Freeport and the San Joaquin River at Vernalis during the 1997 flood.

At Vernalis, the river stage was not influenced by tide and thus, the river stage is solely determined by the San Joaquin River flow. However, at Jersey Point (RSAN018), the river stage was constantly affected by the tides, as indicated by the zigzag pattern of river stage present throughout the three-month period shown in Figure III-8. On January 3 through 5, when the flood flows reached their peaks in both major tributaries, the tidal effect was still strong enough to cause the river stage to oscillate with about one foot of amplitude. Although the amplitude was largely reduced from the 4 feet observed in the early December of 1996, the stage oscillation is still clear. The stage oscillation is reduced because the space in the river channel vacated by tide recess was filled instantly by the flood flows from the tributaries. In addition, the river stage at Jersey Point is more correlated to the Sacramento River flow at Freeport than to the San Joaquin River flow at Vernalis. The second flood peak of the Sacramento River in late January is reflected by the river stage at Jersey Point, while the San Joaquin River flow at Vernalis was relatively constant during that period of time.

The stage records of the Stockton Ship Channel at Burns Cutoff (RSAN058) are not available after December 31, 1996. Based on the available records, the tidal effects are evident at this location and the stage variation is similar to that of the San Joaquin River at Jersey Point.

At the upstream location at Brandt Bridge (RSAN072), the tidal effects are observed for most of the period from December 1996 through February 1997; however, the stage oscillation due to tidal influences is small compared to the river stage increase caused by the flood flow. Compared to the downstream stations, river stage at Brandt Bridge has a much higher correlation to that at Vernalis.

Old River

Stage records along the Old River during the 1997 flood are available at Old River at Head (ROLD074), Old River at Tracy Boulevard (ROLD059), Grant Line Canal at Tracy Boulevard (CHRGL009), Old River at Byron, CCWD Pumping Station (ROLD034), and Old River at Bacon Island (ROLD024). Figure III-9 shows the comparison of river stages at these locations.

Tidal effects are evident at locations downstream from Tracy Boulevard. At the head of the Old River, the tidal effects were suppressed by the flood flow after the recorded flow at Vernalis reached about 30,000 cfs. The river stages of Old River at Head (ROLD074), Old River at Tracy Boulevard (ROLD059), and Grant Line Canal at Tracy Boulevard (CHRGL009) appear to be more influenced by the San Joaquin River flow at Vernalis where stages at remaining downstream locations are more stable and seem to have more correlation to the Sacramento River flow.

Middle River

The Middle River splits flow from the Old River at Union Island. Stage records along the Middle River during the 1997 flood are available at Middle River at Mowry Bridge (RMID040), Middle River at Tracy Boulevard (RMID027), Middle River at Borden Highway (RMID023), and Middle River at Middle River (RMID015). However, the records of Middle River at Mowry Bridge are missing during the high flow period. Figure III-10 shows the comparison of river stages at these locations.

While tidal effects are evident in all the available stage data for Middle River, San Joaquin River flows appear to have less influence on the river stage after Middle River passes the Borden Highway (Highway 4).

Sensitivity of Stages in Delta Waterways

The river stage at any location in the Delta is a result of tidal flow and concurrent flows from the Sacramento River, the San Joaquin River, and east-side tributaries. The locations where the tide solely determines the river stage may only exist in the San Francisco Bay, and locations where the flood flows solely determine the river stages may exist only at the upstream point (such as Vernalis) beyond the Delta backwater influence. The stage at any location in between will be determined jointly by all inflows (including tides).

For the 1997 Flood, the stage records suggest that the San Joaquin River flow has significantly less influence on the river stages at and downstream from Stockton Ship Channel at Burns Cutoff (RSAN058), Middle River at Tracy Boulevard (RMID027), and Old River at Byron, CCWD Pumping Station (ROLD034). There are no data available along the Old River to refine the location between Old River at Byron (ROLD034) and Old River at Tracy Boulevard (ROLD059). Although the exports at the South Delta may influence the hydraulic balance in their vicinity; however, in the 1997 Flood, the export was small compared to the magnitude of floodwater coming into the Delta.

The 1997 Flood is classified as an 89-year event for 1-day duration of San Joaquin River flow at Vernalis (*Comprehensive Study In-Progress Review Report, Appendix A: Synthetic Hydrology Technical Documentation*, October 2000). When a flood with a higher or lower return period (ranging from 10 to 500 years for this study) is considered, the area where the San Joaquin River flow has little influence on river stage will move upstream or downstream from the area for the 1997 flood. The extent of the movement cannot be clearly defined without specifying the concurrent tidal flows and flows from the Sacramento River and eastside tributaries.

FIGURE III-7

REAL-TIME RIVER STAGES IN THE SACRAMENTO RIVER DURING THE 1997 FLOOD

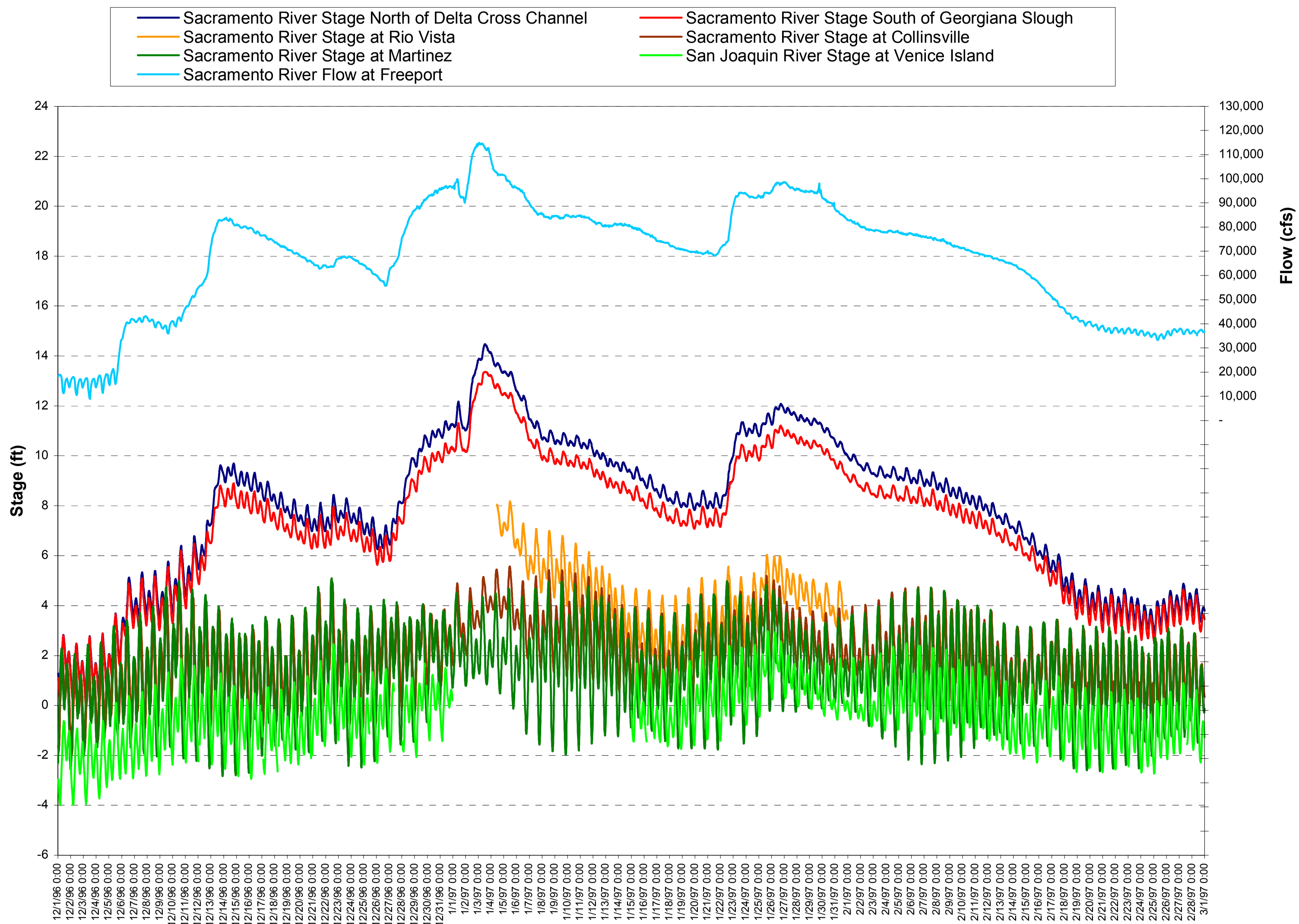


FIGURE III-8

REAL-TIME RIVER STAGES IN THE SAN JOAQUIN RIVER DURING THE 1997 FLOOD

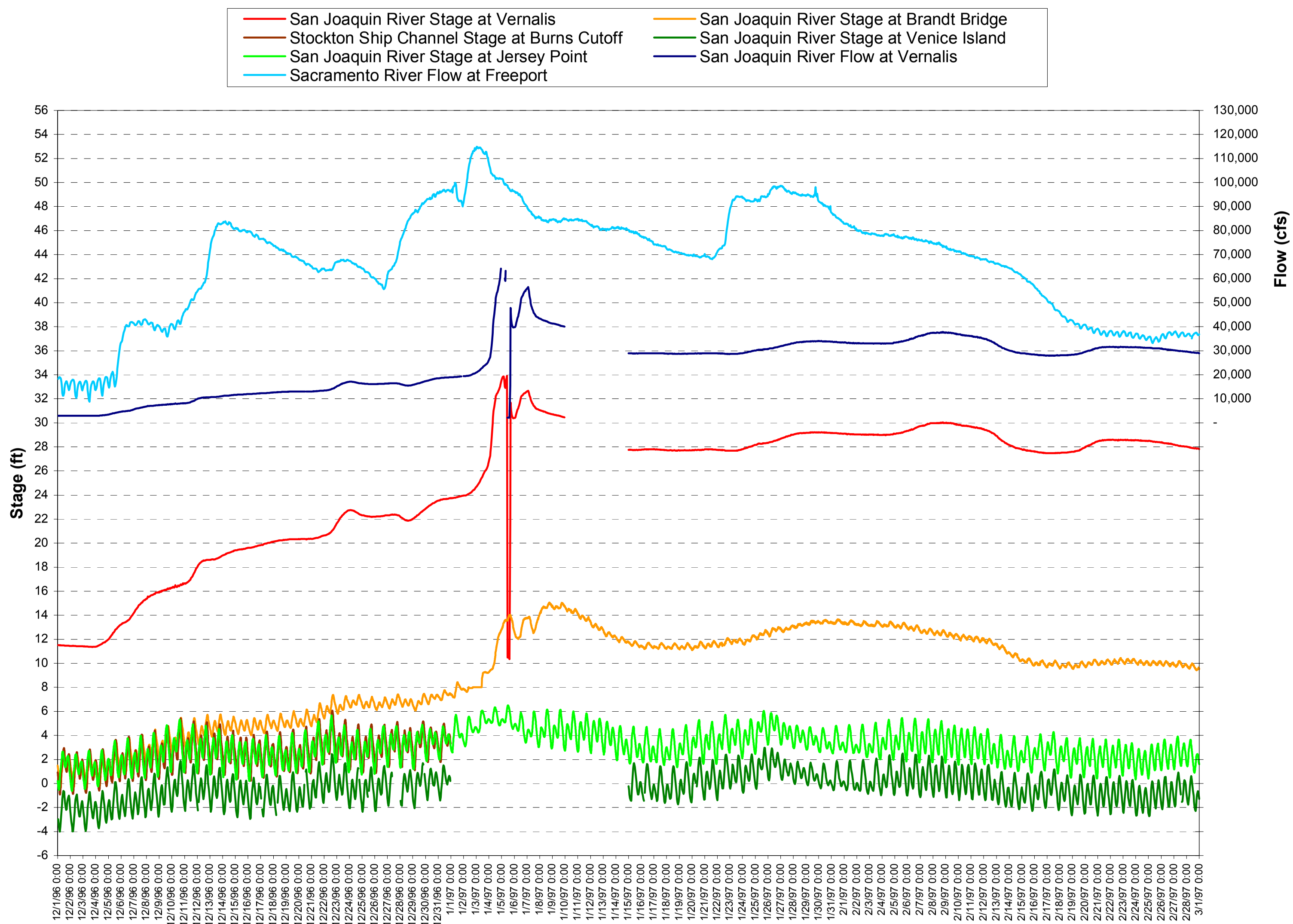


FIGURE III-9

REAL-TIME RIVER STAGES IN THE OLD RIVER DURING THE 1997 FLOOD

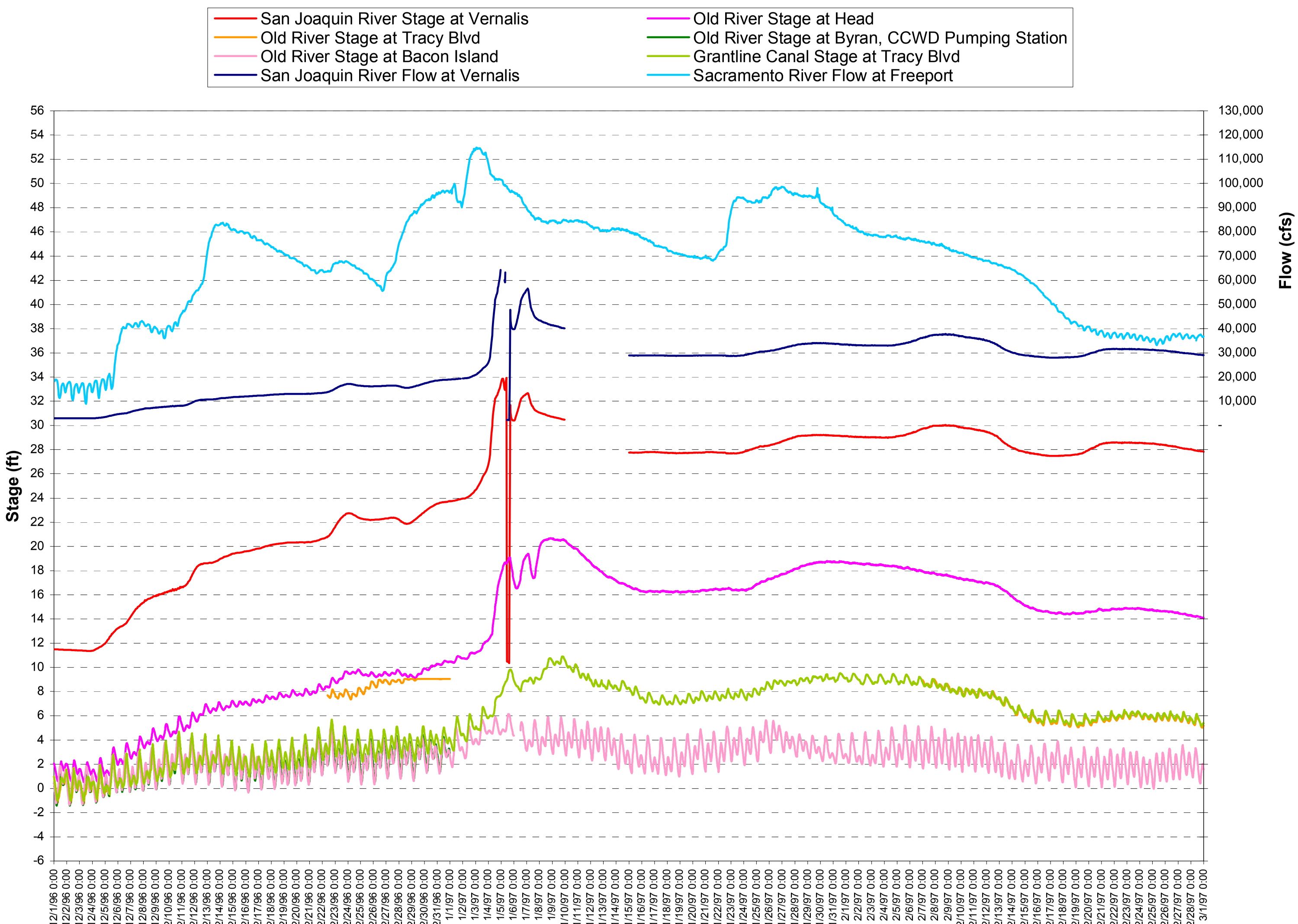
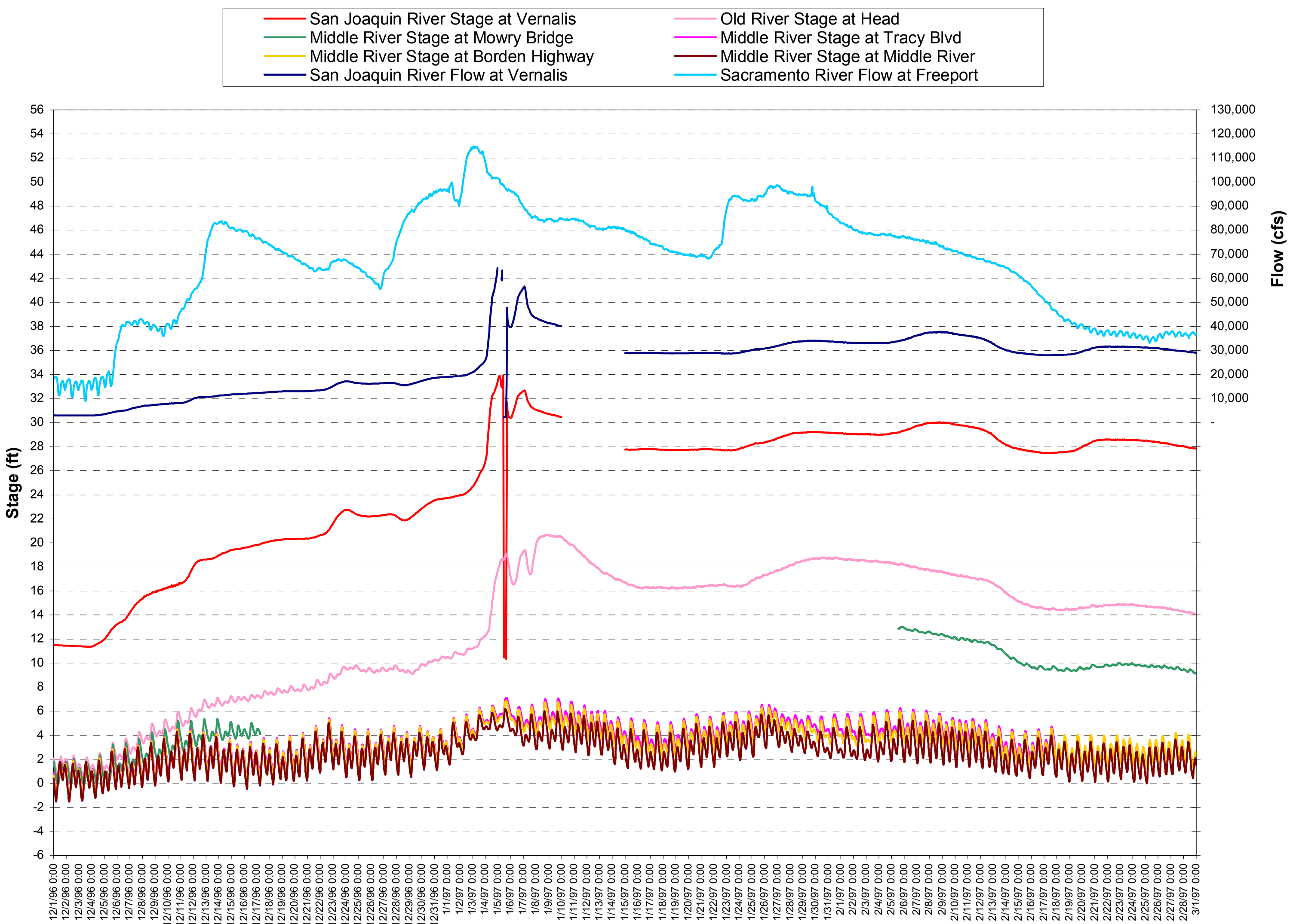


FIGURE III-10

REAL-TIME RIVER STAGES IN THE MIDDLE RIVER DURING THE 1997 FLOOD



CHAPTER IV

DELTA HYDRODYNAMICS MODELING

Three one-dimensional hydrodynamic models are used in the Comprehensive Study: Sacramento River UNET model (SACUNET), San Joaquin River UNET model (SJRUNET) and Delta Simulation Model II (DSM2). SACUNET and SJRUNET were developed by the Corps, and DSM2 was developed by the DWR. Separate technical documents have been prepared for the SACUNET and SJRUNET to detail the model components, features, and initial and boundary conditions. DSM2 model descriptions and the joint operation with two UNET models will be discussed in detail in this chapter.

SACRAMENTO RIVER UNET MODEL

SACUNET covers the area from the north Delta to the hydrologic-hydraulic handoff points along the major tributaries of the Sacramento River. These tributaries include Miner Slough, American River, Natomas East Main Drain, Feather River, Bear River, Yuba River, Yolo Bypass, Colusa Drain, Sacramento Bypass, Sutter Bypass, Butte Slough, and Tisdale Bypass. The downstream boundaries of SACUNET are the following locations: Sacramento River at Collinsville, the downstream end of the Three Mile Slough, and the downstream end of the Georgiana Slough. That is, the project levees in the north Delta are covered in the modeling area.

See *Hydraulic Technical Documentation*, *In-Progress Review Report: Appendix C* for details. Also see *Synthetic Hydrology Technical Documentation*, *In-Progress Review Report: Appendix A* and *Reservoir Operations Modeling*, *In-Progress Review Report: Appendix B* for hydrology development and reservoir simulation that provide inputs for the SACUNET.

SAN JOAQUIN RIVER UNET MODEL

SJRUNET covers the area from the south Delta to the hydrologic-hydraulic handoff points along the major tributaries of the San Joaquin River. These tributaries include Little Johns Creek, Stanislaus River, Dry Creek (a tributary to Tuolumne River), Tuolumne River, Del Puerto Creek, Orestimba Creek, Merced River, Los Banos Creek, Bear Creek, Owens Creek, Ask Slough, Berenda Slough, Fresno River, James Bypass, and Fresno Slough. The downstream boundaries of SJRUNET are the following locations: San Joaquin River at Burns Cutoff, Old River at Tracy Boulevard, Middle River at Highway 4, and Grant Line Canal at Tracy Boulevard. That is, the project levees in the south Delta are included in the modeling area.

See *Hydraulic Technical Documentation*, *In-Progress Review Report: Appendix C* for details. Also see *Synthetic Hydrology Technical Documentation*, *In-Progress Review Report: Appendix A* and *Reservoir Operations Modeling*, *In-Progress Review Report: Appendix B* for hydrology development and reservoir simulation that provide inputs for the SJRUNET.

DELTA SIMULATION MODEL II

DSM2 General

DWR developed DSM2 based on the USGS's FourPt model for hydrodynamics and Branch Lagrangian Transport Model for water quality. DSM2 can calculate water stage, flow, and velocity in the Delta waterways under tidal influences and local consumptive use, CVP-SWP operations, and flow management operations for ecosystem protections. These hydrodynamic results facilitate the evaluation of mass transport processes for salts, non-conservative constituents, temperature, THM formation potential and individual particles. The portion of DSM2 used in the Comprehensive Study is the hydrodynamic module.

The modeling area of DSM2 includes all areas in the legal Sacramento-San Joaquin Delta. DWR has completed a re-calibration for DSM2 in year 2000 through an IEP effort to incorporate major upgrades in model resolution, data management, and utility features. The flow boundaries at the following locations: San Joaquin River at Vernalis, Sacramento River at I Street, Yolo Bypass at Shag Slough, Consumnes River at Franklin Road, Mokelumne River at Franklin Road, Calaveras River at San Joaquin River. At the downstream end, DSM2 uses the tide stages at Martinez as the downstream boundary conditions. DSM2 also incorporates the consumptive use in the Delta, and the exports of the Central Valley Project and the State Water Project.

DSM2 for Flood Simulations

Validation: 1997 Flood Simulation

The DSM2 was originally designed to simulate hydrodynamic and water quality conditions in the Delta under normal flow conditions, i.e., non-flooding condition. The Comprehensive Study provides an opportunity for DSM2 to simulate flooding conditions in the Delta. For a test run, DWR staff conducted a simulation run of the 1997 Flood using available historical data. The simulation results are attached as Appendix A. Based on the simulation results, DWR staff reached the following conclusions:

- The historical records of San Joaquin River flow at Vernalis after January 4, 1997 may be erroneous. (The San Joaquin River flows at Vernalis serve as boundary conditions in the DSM2.) The flow peak may be overstated and the third flood peak appears to be missing in the records. As a result, the simulated river stages show significant discrepancies from the historic records at many locations in the south and central Delta.

- The simulation results using the existing DSM2 model (the re-calibrated year 2000 version) are satisfactory after the data anomaly of San Joaquin River flow at Vernalis is removed. A regression analysis, which correlates the San Joaquin River flow at Vernalis and the river stage of San Joaquin River at Brandt Bridge (38 miles downstream from Vernalis), was used to synthesize a possible hydrograph of the San Joaquin River at Vernalis after January 4. The adjusted San Joaquin River flows at Vernalis are obtained by using the regression formula, the historical records of river stage at Brandt, and the average tide. The synthesized hydrograph of San Joaquin River at Vernalis was then used as the boundary condition in the model simulation. The results show significant improvements in river stage prediction in the Delta.

- The existing DSM2, which was calibrated to normal flow conditions, is adequate for the use in the Comprehensive Study. The results of DSM2 simulation for the 1997 Flood are satisfactory after the data anomaly in the San Joaquin River flow at Vernalis is removed.

Limitations of DSM2 for Flood Simulations

The validation of using DSM2 in flooding conditions was successful; however, the DSM2 still has limitations when applied to flood simulations. These limitations include:

- DSM2 cannot simulate levee breaks and out-of-channel flows.
- DSM2 assumes that a vertical wall on each side of the channel that can contain channel flows indefinitely. Therefore, levee over-topping is not represented.
- DSM2 does not have routines for hydrodynamic calculations near bridges.

These limitations result from the basic assumptions used in the model, and these assumptions are suitable for DSM2's intended applications: simulations of Delta hydrodynamic and water quality conditions under normal flow conditions. In some extreme events, however, these limitations may result in unrealistic hydrodynamic conditions in the Delta. Thus, for the Comprehensive Study, the results of DSM2 simulations are used strictly for scenario comparison only, and no specific assessments on levee safety and configuration will be made based on these results.

DSM2 Model Sensitivity

Model sensitivity is used to evaluate the relative changes of a certain measurement (e.g., river stage in the Delta) with respective to the changes in a boundary condition or other controlling factors (e.g., San Joaquin River flow). If the model sensitivity is low, the change in the controlling factor has a relative small impact on a model output. Model sensitivity can also be used to define the relative importance of each controlling factor in the determination of the stage at any interested location in the Delta to supplement the deficiency of historical data. The DSM2 simulation for the 1997 Flood was used in a model sensitivity review.

DWR staff determined that the historical records of San Joaquin River at Vernalis after January 4, 1997 are erroneous. Compared to the historical records, the "corrected" hydrograph of the San Joaquin River at Vernalis shows a roughly 2,000-cfs reduction in the flood peak on January 5, a restored flood peak of 35,000 cfs on January 9, and elevated flows after January 8.

Comparison of the simulation results before and after the "correction" indicates the sensitivities of river stage at various locations in the Delta to the changes in the San Joaquin River flow.

Hydrographs and stage histograms at selected locations in the Delta under the historical and corrected hydrographs of the San Joaquin River were provided by DWR staff and compiled in Attachment A. The comparison of these two sets of calibration results suggests the following model sensitivity to the change in the San Joaquin River flow.

- **Locations with Low Sensitivity.** The change in the San Joaquin River flow does not cause any visible difference in the stage. These locations include Stockton Ship Channel at Burns Cutoff (RSAN058), San Joaquin River at Jersey Point (RSAN018), San Joaquin River at Antioch (RSAN007), Old River at Bacon Island (ROLD024), Middle River at Middle River (RMID015), Middle River at Bacon Island (RMID007), Sacramento River at North of Delta Cross Channel (RSAC128), Sacramento River at Rio Vista (RSAC101), and Sacramento River at Collinsville (RSAC081).

- **Locations with Moderate Low Sensitivity.** The change in the San Joaquin River flow causes minor change in the river stage, and the erroneous peak flow was not reflected by the river stage in the original simulation with the unadjusted San Joaquin River flow. These locations include CCWD Intake (ROLD034), and Middle River at Highway 4 (RMID023).

- **Locations with Moderate High Sensitivity.** The change in the San Joaquin River flow causes minor change in the river stages, and a more prominent change in the peak flow. These locations include San Joaquin River at Stockton (RSAN063), Old River near DMC, SE of Barrier (ROLD047), and Old River near DMC, NW of Barrier (ROLD046).

- **Locations with High Sensitivity:** The simulated river stage changes significantly after the modification of the San Joaquin River flow. These locations include San Joaquin River at Brandt Bridge (RSAN072), Old River at Head (ROLD074), Old River at Tracy Boulevard (ROLD059), and Middle River at Tracy Boulevard (RMID027).

For the 1997 flood, the area that the correction of the San Joaquin River flow have little impact on the river stage (i.e., the area defined by the low sensitivity group) is downstream from Stockton Ship Channel at Burns Cutoff (RSAN058), Middle River at Highway 4 (RMID023), and Old River at CCWD Intake (ROLD034).

DSM2 Customization for the Comprehensive Study

Reduced Modeling Area

The modeling area of DSM2 was reduced for the Comprehensive Study to cover only the areas in the Delta that are outside of SACUNET and SJRUNET modeling areas. This model reduction was determined to be necessary because DSM2 does not simulate levee failures and hydrodynamic conditions around bridges. The modeling areas of SACUNET and SJRUNET cover portions of the Delta where the project levees are located and therefore, it is advantageous to use UNET models for these areas so that the evaluations of system performance can be consistent for the Comprehensive Study.

Two alternatives to the reduction of DSM2 were considered: the reduction of SACUNET and SJRUNET to preserve the modeling area of DSM2, and no modeling area reduction for any of SACUNET, SJRUNET and DSM2 but allowing overlapping modeling areas in the north and south Delta. The main concerns for the former alternative is that the project levees in the Delta cannot be properly evaluated, and the model resolution of DSM2 in those areas is not consistent to the upstream areas modeled by UNET. In the latter alternative, DSM2 would take the UNET outputs at Vernalis (SJRUNET), Freeport (SACUNET), and Yolo Bypass (SACUNET). Although the integrity of each model is preserved, the results would be confusing. Two sets of results from UNET and DSM2 in the overlapping areas would be very different, resulting from significantly different assumptions and capabilities in simulating flooding. In addition, because of DSM2's limitations in simulating levee failures in the south and north Delta areas (the upstream reaches for DSM2), the resulting downstream Delta hydrodynamics may not properly correspond to the scenarios intended for UNET modeling.

The reduced DSM2 covers most of the non-project levees locate in the Delta. The upstream boundaries are the downstream boundaries of UNET models; that is, Sacramento River at Collinsville, the downstream end of the Three Mile Slough, the downstream end of the Georgiana Slough, San Joaquin River at Burns Cutoff, Old River at Tracy Boulevard, Middle River at Highway 4 and Grant Line Canal at Tracy Boulevard. The original upstream boundaries for eastside streams remain unchanged: Consumnes River at Franklin Road, Mokelumne River at Franklin Road, and Calaveras River at San Joaquin River. The downstream boundary of the reduced DSM2 remains at Martinez.

Derivation of Upstream Boundary Conditions

The Comprehensive Study has developed a methodology to synthesize hydrology in the Central Valley that accounts for possible variation in storm centering. The center of a storm can be an upstream tributary area, a location on the mainstem of Sacramento River or San Joaquin River, or at the Delta. The details of the synthetic hydrology are available in *Synthetic Hydrology Technical Documentation*, *In-Progress Review Report: Appendix A* (Comprehensive Study, 2000).

For the simulation in the Delta, the Comprehensive Study focuses on storms of Sacramento River centering (at Sacramento), San Joaquin River centering (at Vernalis), and Delta centering. These storms are expected to create significant regional impacts and produce large runoff volumes throughout the system. For each storm, the concurrent hydrology developed for the Sacramento and San Joaquin Valley was used in the reservoir operations and consequently, the UNET model simulation to generate outflows at the downstream boundaries of UNET models. These flows become the upstream boundary conditions for DSM2 simulations. The concurrent hydrology developed for the Delta eastside tributaries (Consumnes River, Mokelumne River, and Calaveras River) is applied to DSM2 directly.

Derivation of Downstream Boundary Conditions

One of the most challenging tasks for DSM2 simulations is the determination of a proper downstream boundary condition at Martinez for synthetic storm events. As mentioned in previous chapters, tides are governed by planetary movements of the sun, the moon, and the earth. The frequency analysis often used for surface water hydrology is not applicable. Several possible downstream boundary conditions have been suggested including the long-term average tidal ranges, and the historical tidal ranges in the 1997 Flood.

After examining the historical tidal ranges and the net Delta outflow during flooding conditions, DWR determined that the historical tidal ranges in the 1997 Flood are representative and can be applied to all flooding events currently considered by the Comprehensive Study. This conclusion was drawn from a net Delta outflow analysis conducted by DWR. The analysis focused on possible stage variation at Martinez during different flood events. The net Delta outflows (flows at Martinez) greater than 200,000 cfs were correlated to the 14-day running averages of the stage at Martinez. The regression analysis suggests that the difference of 14-day running average stages at Martinez for a 100-year and a 500-year event is less than 2 inches. Therefore, it was determined that errors introduced by using the historical tidal ranges in the 1997 Flood as DSM2's downstream boundary conditions for all Comprehensive Study simulations are insignificant. The DWR memorandum that summarizes the findings is provided in Attachment B. As discussed in the previous chapter, the tidal ranges in the 1997 Flood were enhanced by the parallax effect and were at the seasonal height; however, they are not out of ordinary since tidal ranges of similar magnitudes were also observed in 1995.

The simulated 30-day storms used in the Comprehensive Study start at a **generic** January 1, 1900 time frame to avoid confusions with actual historical records. The assumed hydrology distribution, upstream reservoir operations and levee failure scenarios create peak flows from the Sacramento River and the San Joaquin River entering into the Delta around mid January and late January, respectively. (During the 1997 Flood, the arrival times are January 3 and 5, respectively.) DWR has determined that the tidal ranges of the 1997 Flood are adequate for the DSM2 simulations for the Comprehensive Study. However, the timing for neap and spring tides need further evaluation. The new moon in the 1997 Flood occurred around January 9. Therefore, it is necessary to delay the 1997 tidal ranges to match the neap tide to the peak flow from the Sacramento River so that the downstream boundary conditions are more representative.

Other Assumptions

Other assumptions used in the DSM2 simulations for the Comprehensive Study include:

- Consumptive use in the Delta is ignored due to its small magnitude relative to flood flows.
- The Delta Cross Channel is closed, consistent with the current operations.
- CVP-SWP south Delta pumping and all other export diversions are stopped because it is unlikely to speculate the level of storage in the San Luis Reservoir. Assuming no pumping of excess water would result in conservative estimates of flooding in the Delta.
- All temporary flow barriers in the Delta waterways are removed, consistent with current practice. No permanent flow barriers are assumed.

Based on the discussions presented in the previous chapters, these assumptions are considered adequate and reasonable for the purposes of the Comprehensive Study.

CHAPTER V

SIMULATED DELTA HYDRODYNAMICS IN BASELINE SCENARIOS

BASELINE CONDITIONS AND SCENARIOS

In March 2001, the Comprehensive Study used the baseline conditions defined then to perform a joint study of UNET and DSM2 to evaluate the Delta hydrodynamics. A purpose of this exercise is to go through the process and identify possible problems of using UNET and DSM2 together for the Delta hydrodynamics. Storms of three centerings (Sacramento, Delta and Vernalis) and five return periods (10, 50, 100, 200 and 500 years) are used in this exercise. The assumptions used in SACUNET and SJRUNET allow levee breaks when river stage reaches to certain elevation in the channel (likely failure point), which was developed based on the economical and geotechnical analyses conducted under the Comprehensive Study. These assumptions are transparent to the DSM2 simulations since the only inputs of DSM2 from the upstream UNET models are the flows at the boundary locations.

Simulation results of these baseline scenarios are used in this chapter to further illustrate the hydrodynamics in the Delta. These scenarios are used as examples of Delta hydrodynamic conditions in various storm events. The results are for illustrative purposes, and they are not part of the concept plan development. The discussion in this chapter focuses on DSM2's modeling area.

BOUNDARY CONDITIONS FOR BASELINE SCENARIOS

Delta Inflows

The Delta inflows for the baseline scenarios are from the outflows of SACUNET and SJRUNET, and hydrological analyses for Delta eastside streams. Figures V-1 through V-3 compare these inflows in various storm events.

Figure V-1 shows the inflows of eastside streams, which derive from hydrological analyses performed by the Corps. The inflows appear to be in waves. The combined inflows from Mokelumne and Consumnes Rivers have a peak flow around January 21 for storms with Sacramento River and Delta centerings, and around January 18 for storms with San Joaquin River centering. The multiple and sometimes persistent peak flows of Calaveras River show the basin is in equilibrium (operationally or naturally).

For Sacramento River inflows (SACUNET outflows, shown in Figure V-2), storms of same frequency but different centers produce inflows of similar magnitudes and patterns, although the peak of a San Joaquin River centering arrives earlier. The downstream boundary conditions used in the baseline SACUNET simulations are the adjusted 1997 stage records and thus, tidal influences and daily fluctuations are clearly observed.

Compared with Sacramento River inflows, the differences among San Joaquin River inflows of storms with same frequency but different centerings are more prominent. Figure V-3 shows the comparison. The simulated peak flows of the San Joaquin River arrive at the Delta much later than those of the Sacramento River. These inflows do not show daily fluctuations or tidal influences at the downstream boundaries because stage-discharge rating curves are used as the downstream boundary conditions in these simulations. The stage-discharge rating curves were developed by the Corps based on historical records (with emphasis on data during the 1997 Flood). The use of a stage-discharge rating curve for the downstream boundary condition avoids the difficulties in determining a proper stage hydrograph for study purposes. This may result in some reduction in model resolution near the boundaries.

Connections between UNET and DSM2

As mentioned in Chapter IV, the connections between UNET and DSM2 are based on flows at boundary nodes. The stages at boundary nodes are not adequate for connecting UNET and DSM2 because the channel cross-sections in these two models are not defined identically.

Delta Downstream Stage Boundary

As mentioned in Chapter IV, the adjusted 1997 tidal ranges at Martinez are used as the downstream stage boundary for all DSM2 simulations. The shift in time is based on the comparison between the arrival times of the peak flow from the Sacramento River in the 1997 Flood and the assumed baseline scenarios. Figure V-4 shows the boundary conditions.

DELTA HYDRODYNAMICS FOR BASELINE SCENARIOS

Delta is the converging point of tides and inflows from Sacramento River, San Joaquin River and eastside streams. The stage at a location in the Delta at any time is the result of balancing the currents introduced by these factors. Therefore, the discussion of the hydrodynamic conditions in the Delta is often found to be case specific although some generalization is possible.

The DSM2 simulation results at selected Delta locations for the baseline scenarios are provided in Appendix C. The reporting locations for DSM2 results are shown in Figure V-5. (A summarization of the DSM2 results is also available at http://www.compstudy.org/dsm2/.) A transformation of 25-hour central moving average is performed on the hydrographs to remove most of the daily stage fluctuation caused by tidal influences. Figures V-6 through 5-9 show the 25-hour moving averages of stage at selected Delta locations for selected storm events.

In the baseline scenarios, the peak San Joaquin River inflows arrives at the Delta much later than peak Sacramento River inflows. In addition, the inflows from the eastside streams are in a complete different pattern than those from the Sacramento and San Joaquin rivers. This simulated condition helps to delineate the relative importance of these influence factors in the determination of river stage in the Delta. The dominance of Sacramento River flows and the tidal ranges at Martinez are observed in the comparison of 25-hour moving averages of river stage in the Delta. The stages in the area from Martinez to Jersey Point are predominately controlled by the tidal ranges at Martinez and the Sacramento River flow at Collinsville. To the east, the stages in the central Delta are highly correlated to those of the Georgiana Slough and Three Mile Slough. On the other hand, the boundary conditions (inflows) in the south Delta area have only a limited area of influence in terms of water stage. The influence of San Joaquin River inflows dissipates significantly after several miles from the boundaries near the Clifton Court Forebay although their influence is greater when Delta centering and San Joaquin River centering storms are considered. The influences from the eastside streams are not visible in stage comparison for all events.

The hydrodynamic conditions in the Delta are better illustrated by the stage contour plots shown in Figures V-10 through V-13, which are based on the Sacramento River centering 200-year event. Although variations in magnitude exist, these figures are representative in portraying the Delta hydrodynamics simulated in all baseline scenarios. Note that the contour plots generalize the stage distribution in the Delta without addressing potential localized stage variations, and minor distortion near the boundary may exist due to the limited number of data points used for contouring.

The high stages caused by Georgiana Slough inflows clearly become a major hydraulic barrier for river flows in San Joaquin River and Middle River. The locations of Sacramento River inflows and the Martinez tidal gage are aligned at the north side of the modeling area, establishing the hydraulic grade line that controls the simulated Delta outflows. The peak flows from Sacramento River near January 20 and the concurrent high tides created a high stage condition that is prevalent in the Delta. The south Delta inflows during the high tide condition flow from the Old River to the Middle River and San Joaquin River through the Victoria Canal. On January 25, although the high flows from Sacramento River sustains, the high tide has greatly recessed. Therefore, more flows can be released through Martinez to the ocean, alleviating the high stage condition in the Delta. It is noted that stages in Georgiana Slough are consistently higher than those of nearby locations during the simulation period, which forces more San Joaquin River flow into the Old River. The flows in the Old River increases significantly after the spring tide passes and the south Delta inflows to the Delta increases in the later part of the simulation period. (See Appendix C.)

FIGURE V-1

EASTSIDE STREAM INFLOWS FOR BASELINE SCENARIOS

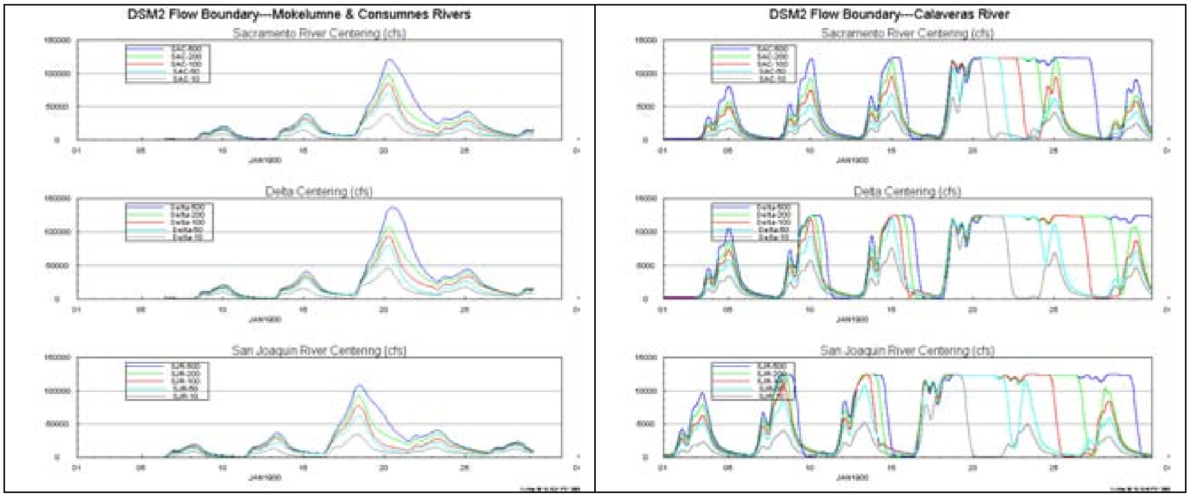


FIGURE V-2

NORTH DELTA INFLOWS FOR BASELINE SCENARIOS (SACUNET RESULTS)

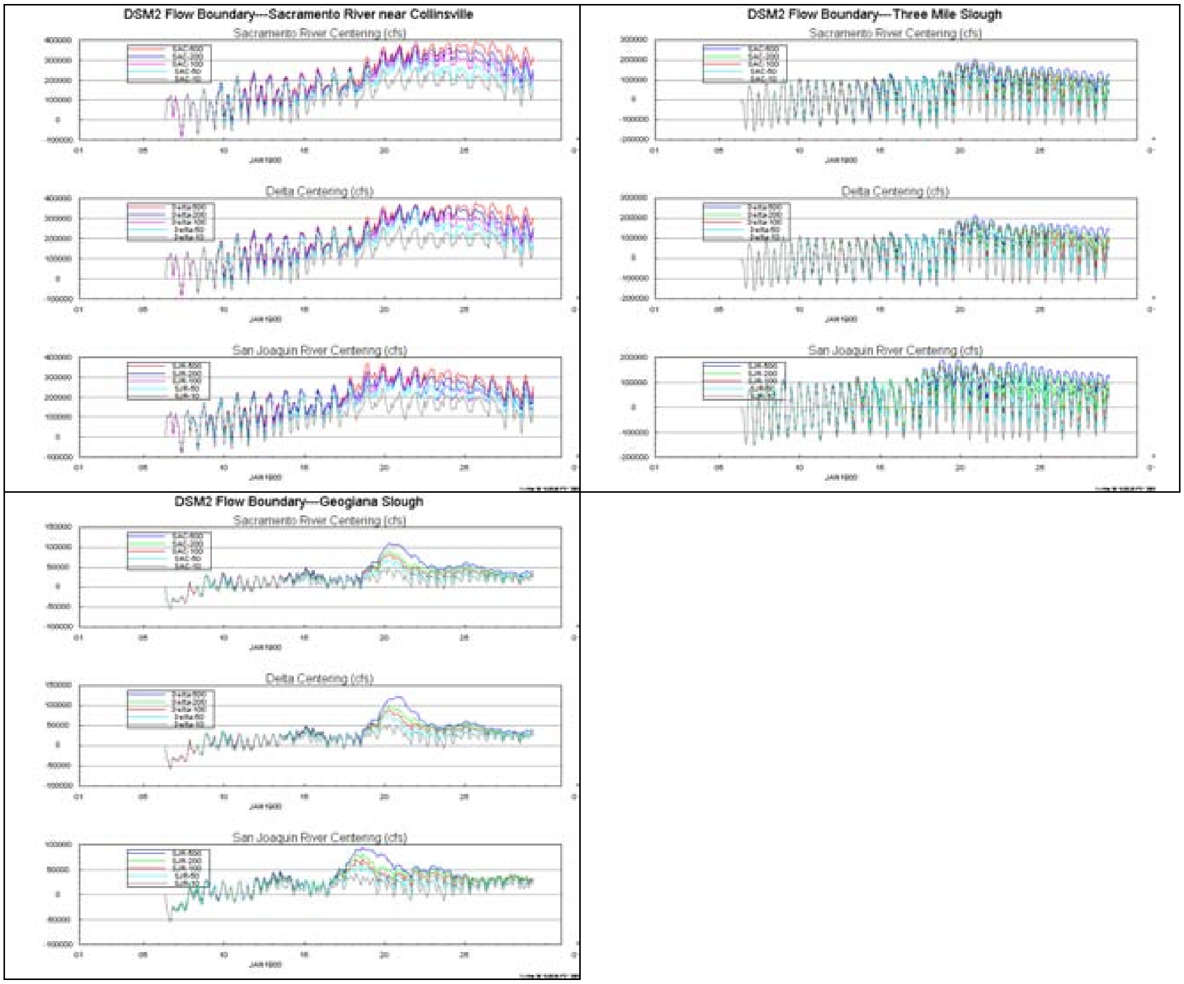


FIGURE V-3

SOUTH DELTA INFLOWS FOR BASELINE SCENARIOS (SJRUNET RESULTS)

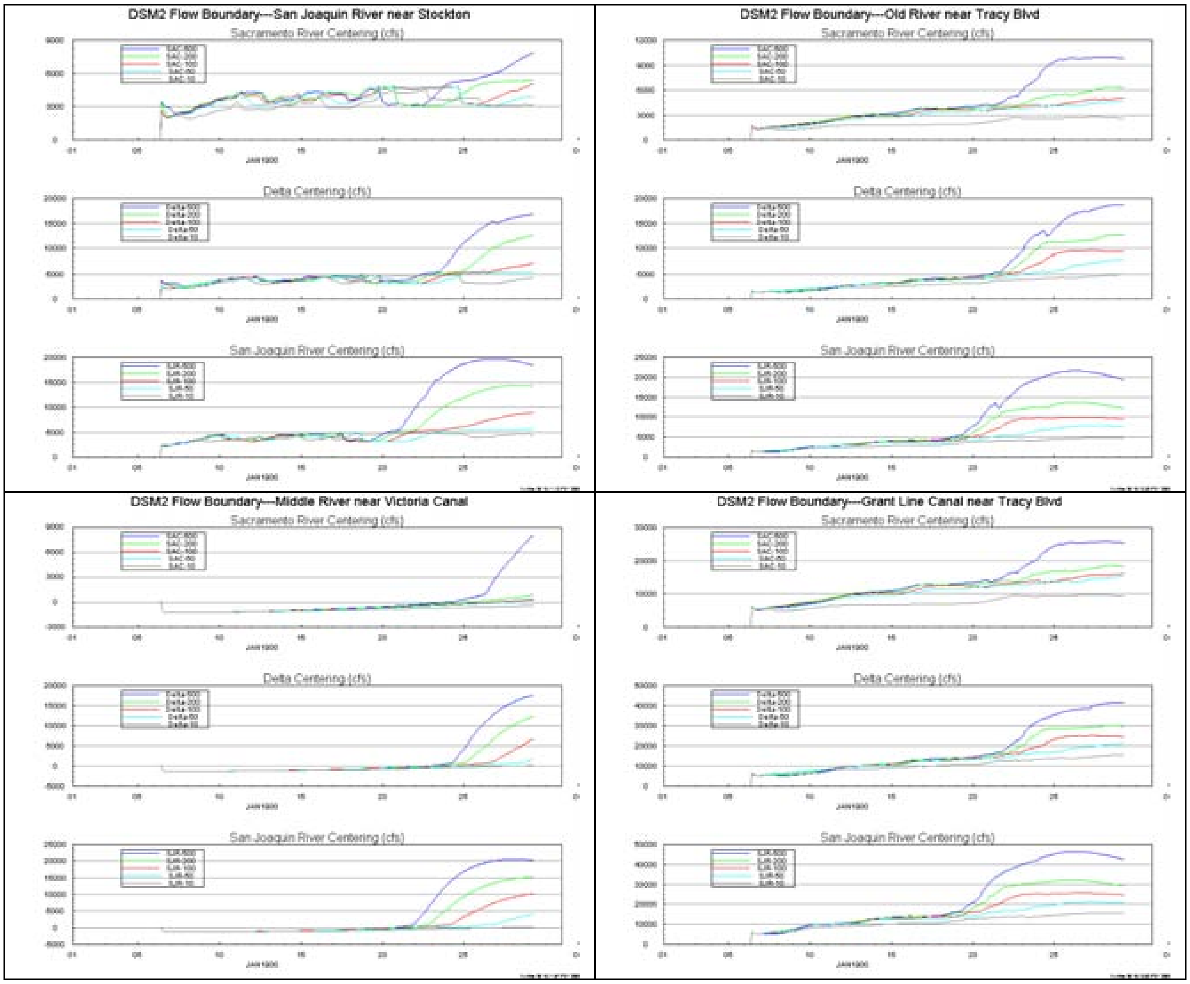


FIGURE V-4

STAGES OF SACRAMENTO RIVER AT MARTINEZ FOR BASELINE SCENARIOS

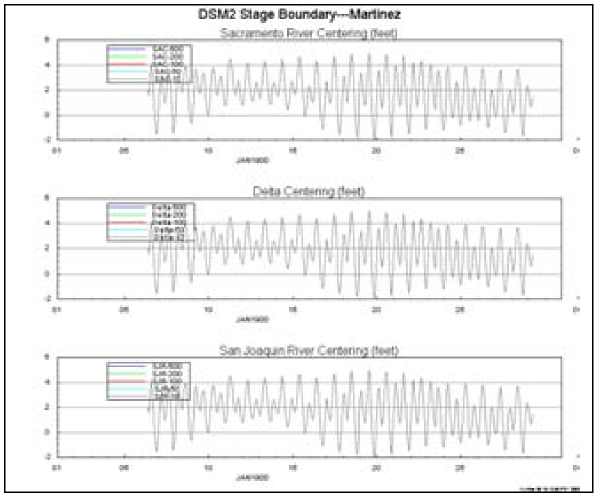


FIGURE V-5

DSM2 REPORTING LOCATIONS

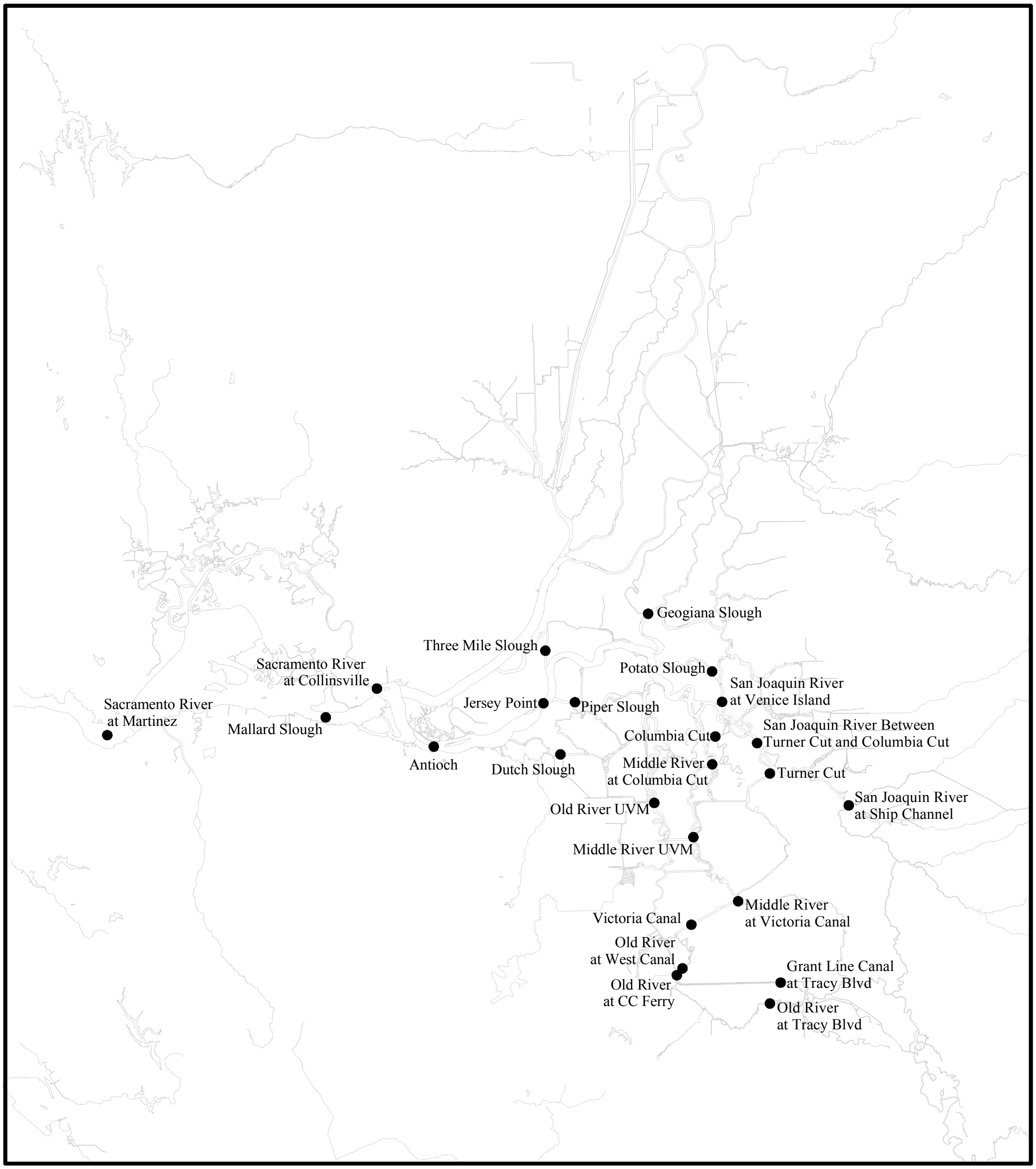


FIGURE V-6

COMPARISON OF 25-HOUR CENTRAL MOVING AVERAGE STAGES IN DELTA WATERWAYS (SACRAMENTO RIVER CENTERING, 100-YEAR EVENTS)

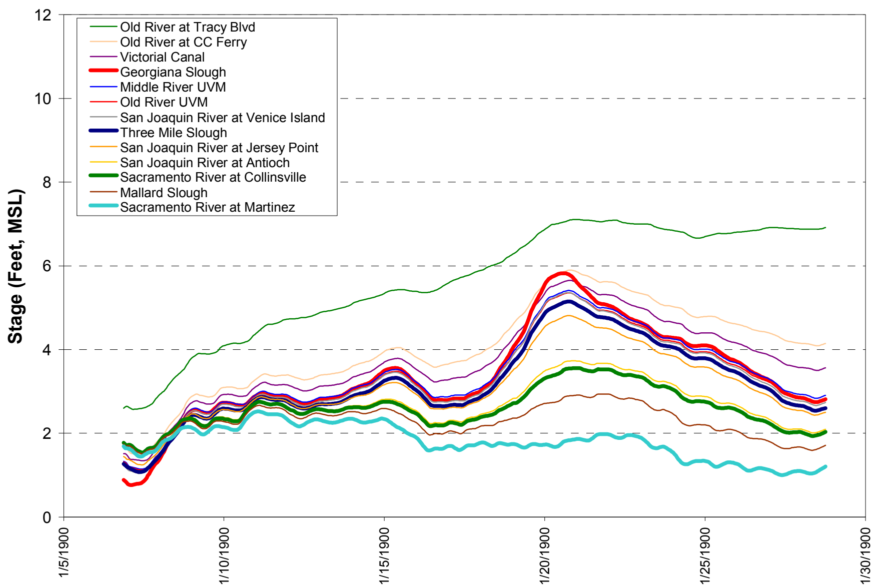


FIGURE V-7

COMPARISON OF 25-HOUR CENTRAL MOVING AVERAGE STAGES IN DELTA WATERWAYS (SACRAMENTO RIVER CENTERING, 200-YEAR EVENTS)

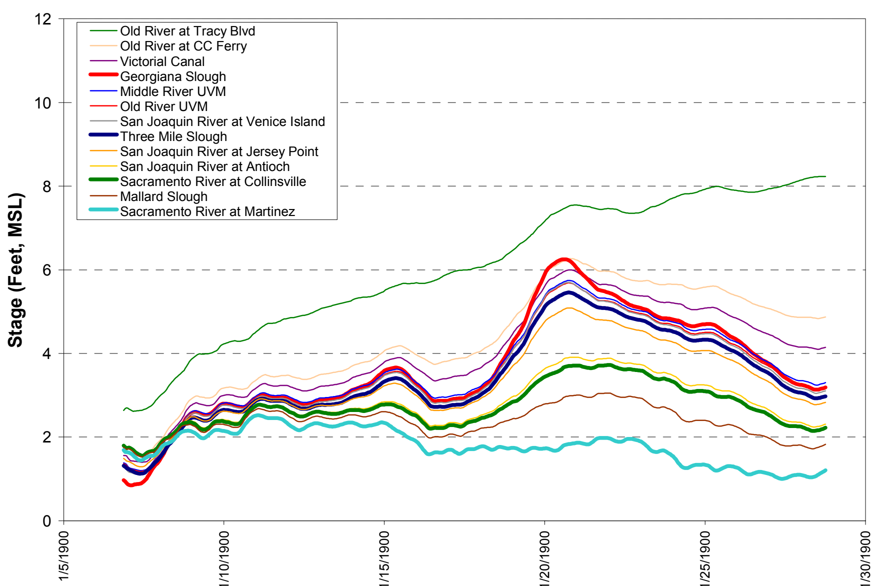


FIGURE V-8

COMPARISON OF 25-HOUR CENTRAL MOVING AVERAGE STAGES IN DELTA WATERWAYS (DELTA CENTERING, 200-YEAR EVENTS)

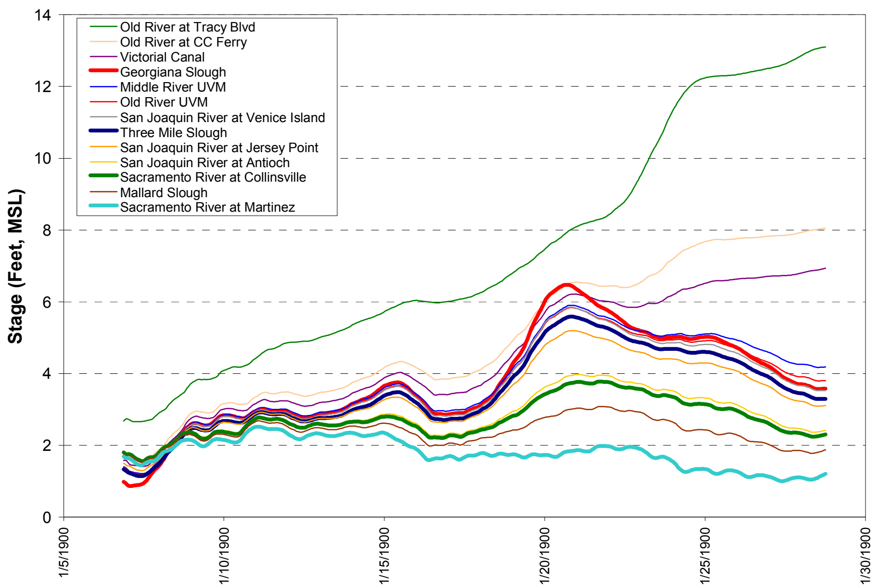


FIGURE V-9

COMPARISON OF 25-HOUR CENTRAL MOVING AVERAGE STAGES IN DELTA WATERWAYS (SAN JOAQUIN RIVER CENTERING, 200-YEAR EVENTS)

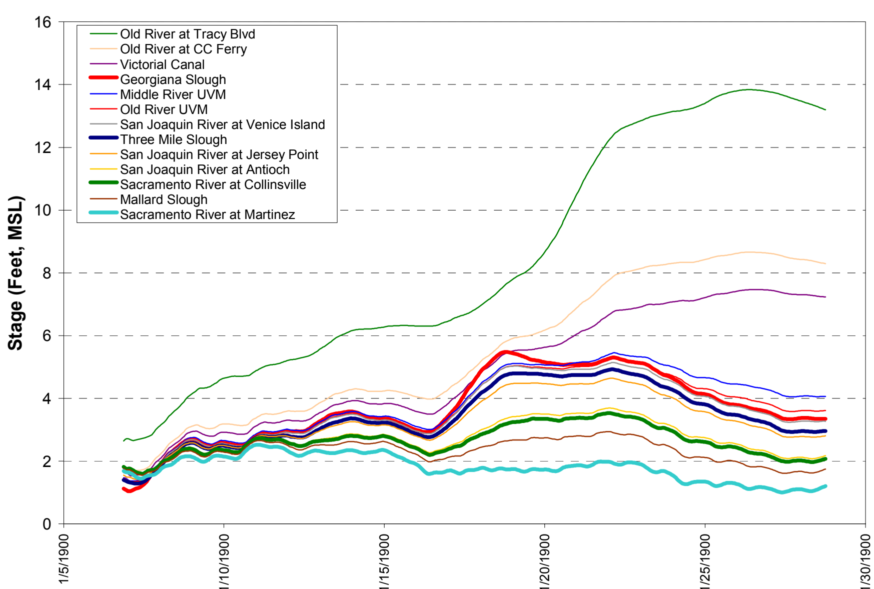


FIGURE V-10

DSM2 RESULTS: 25-HOUR MOVING AVERAGE OF SIMULATED STAGES ON 1/10/1900 FOR SACRAMENTO RIVER CENTERING, 200-YEAR STORM

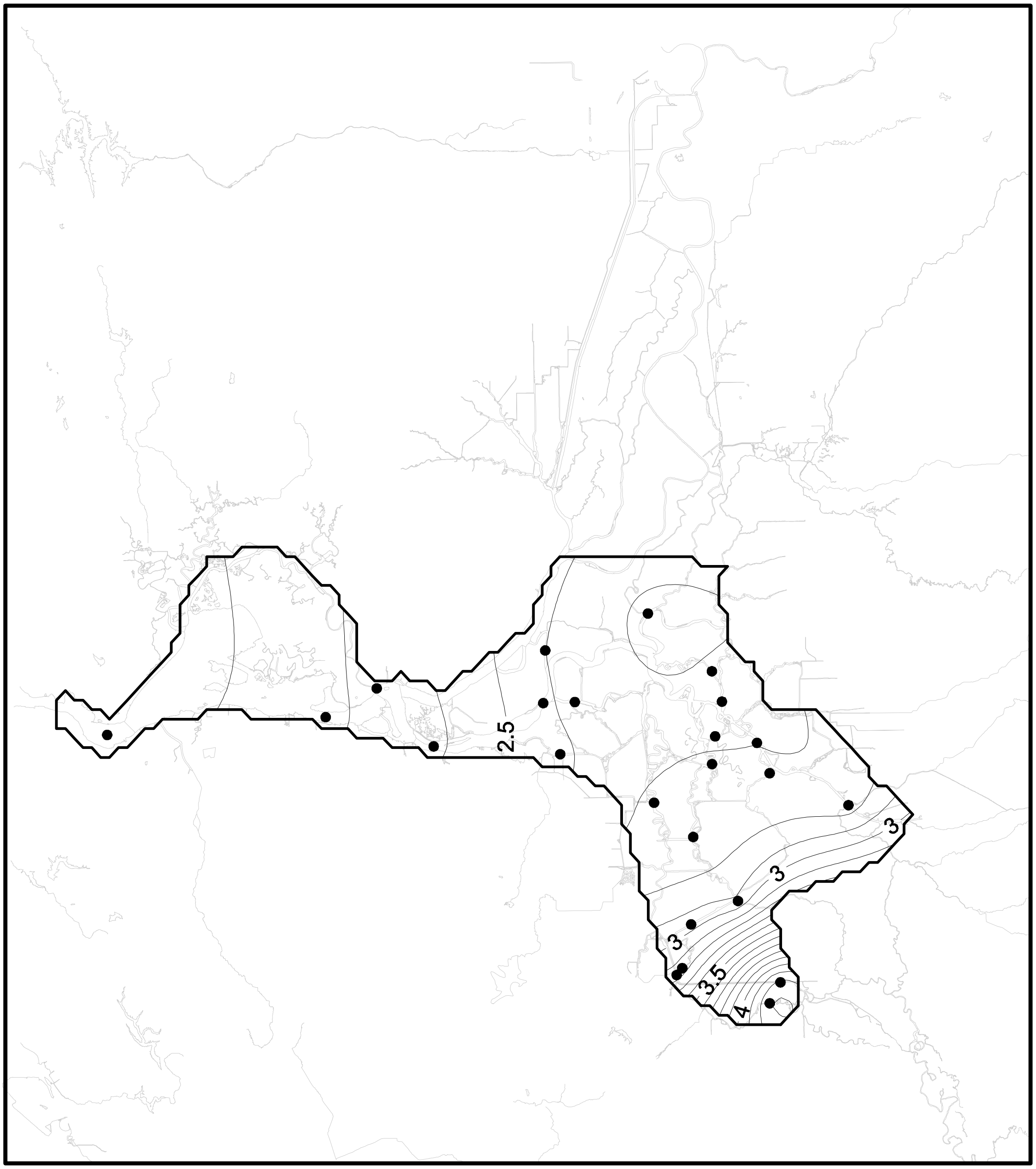


FIGURE V-11

DSM2 RESULTS: 25-HOUR MOVING AVERAGE OF SIMULATED STAGES ON 1/15/1900 FOR SACRAMENTO RIVER CENTERING, 200-YEAR STORM

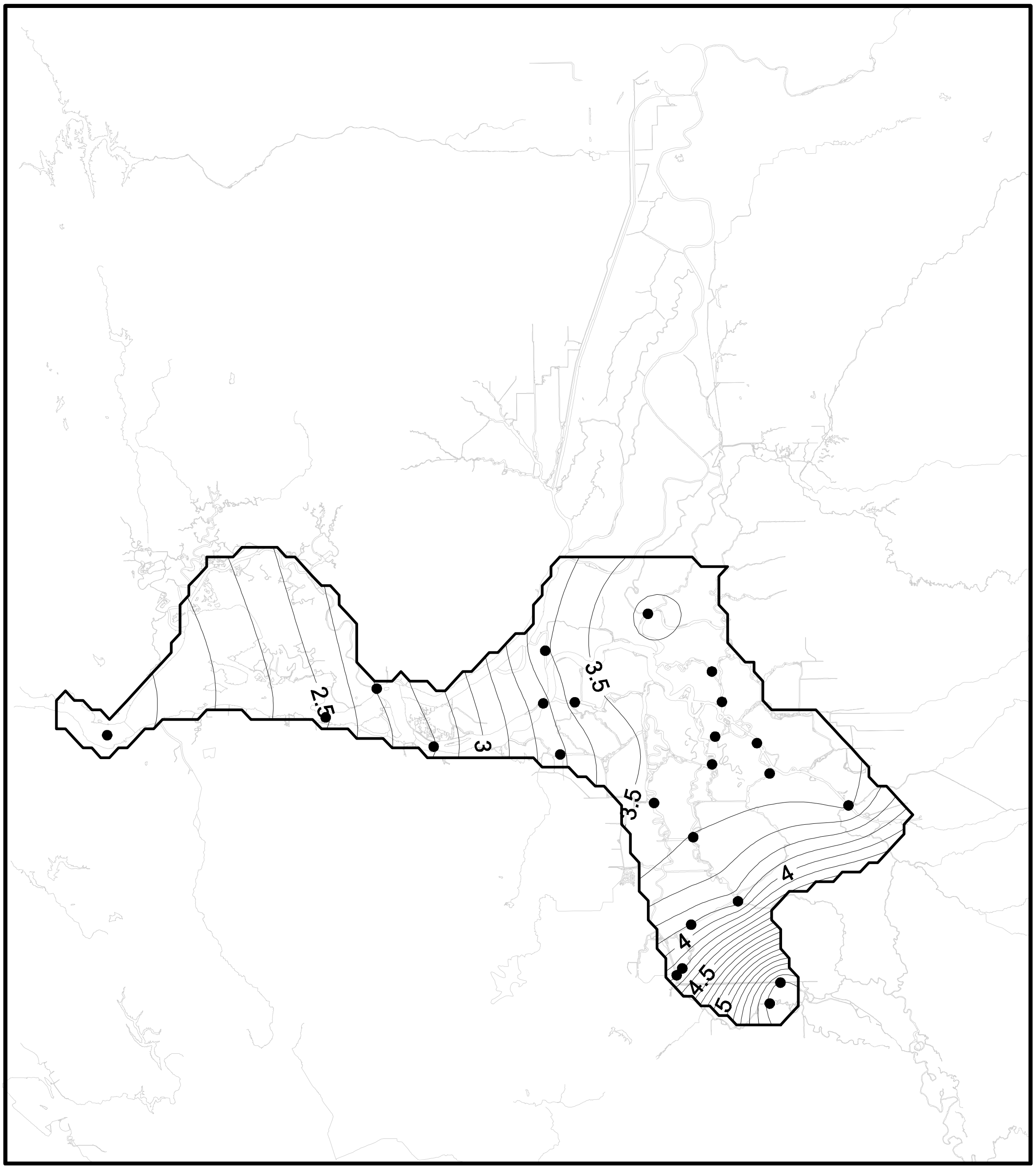


FIGURE V-12

DSM2 RESULTS: 25-HOUR MOVING AVERAGE OF SIMULATED STAGES ON 1/20/1900 FOR SACRAMENTO RIVER CENTERING, 200-YEAR STORM

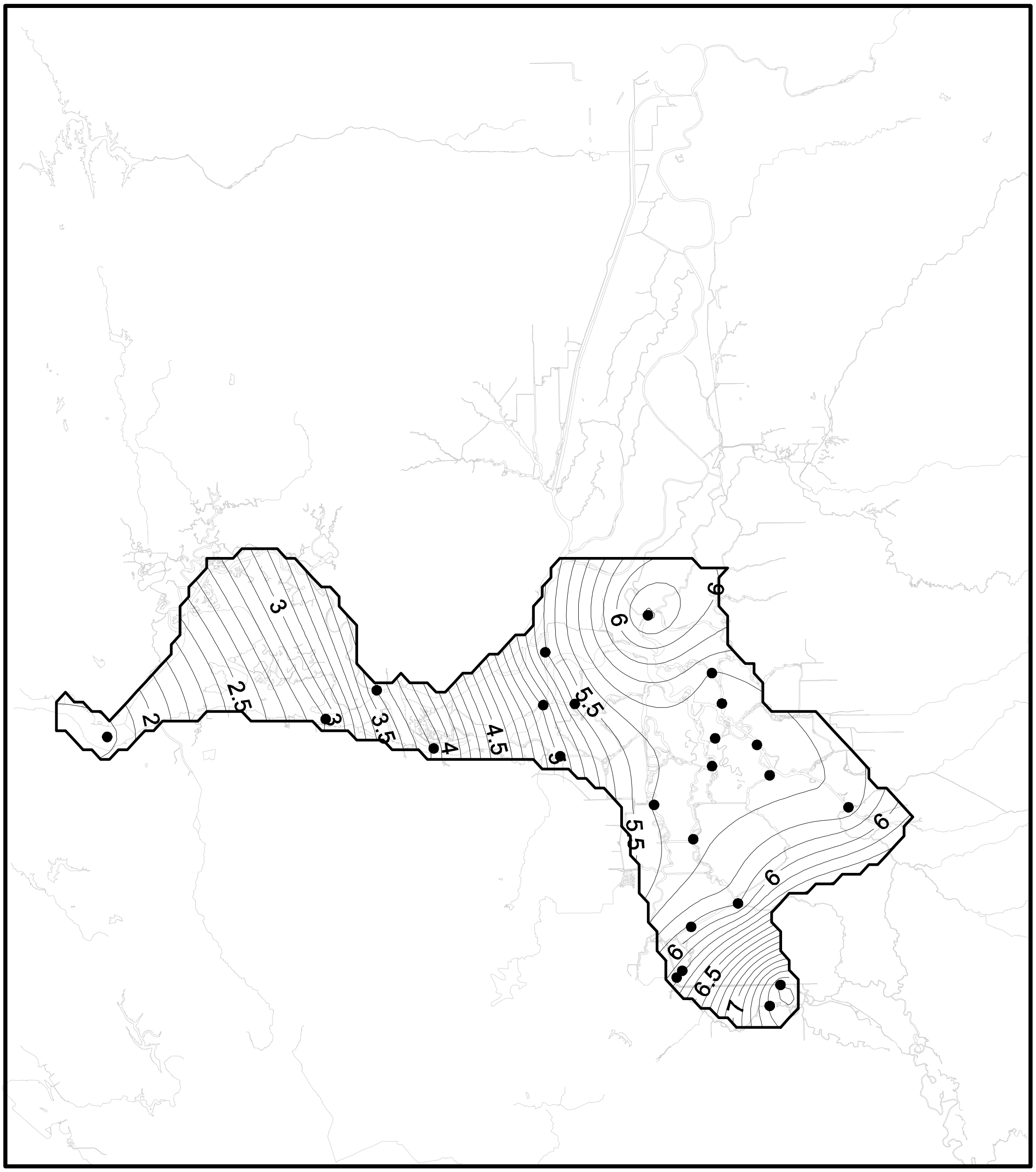
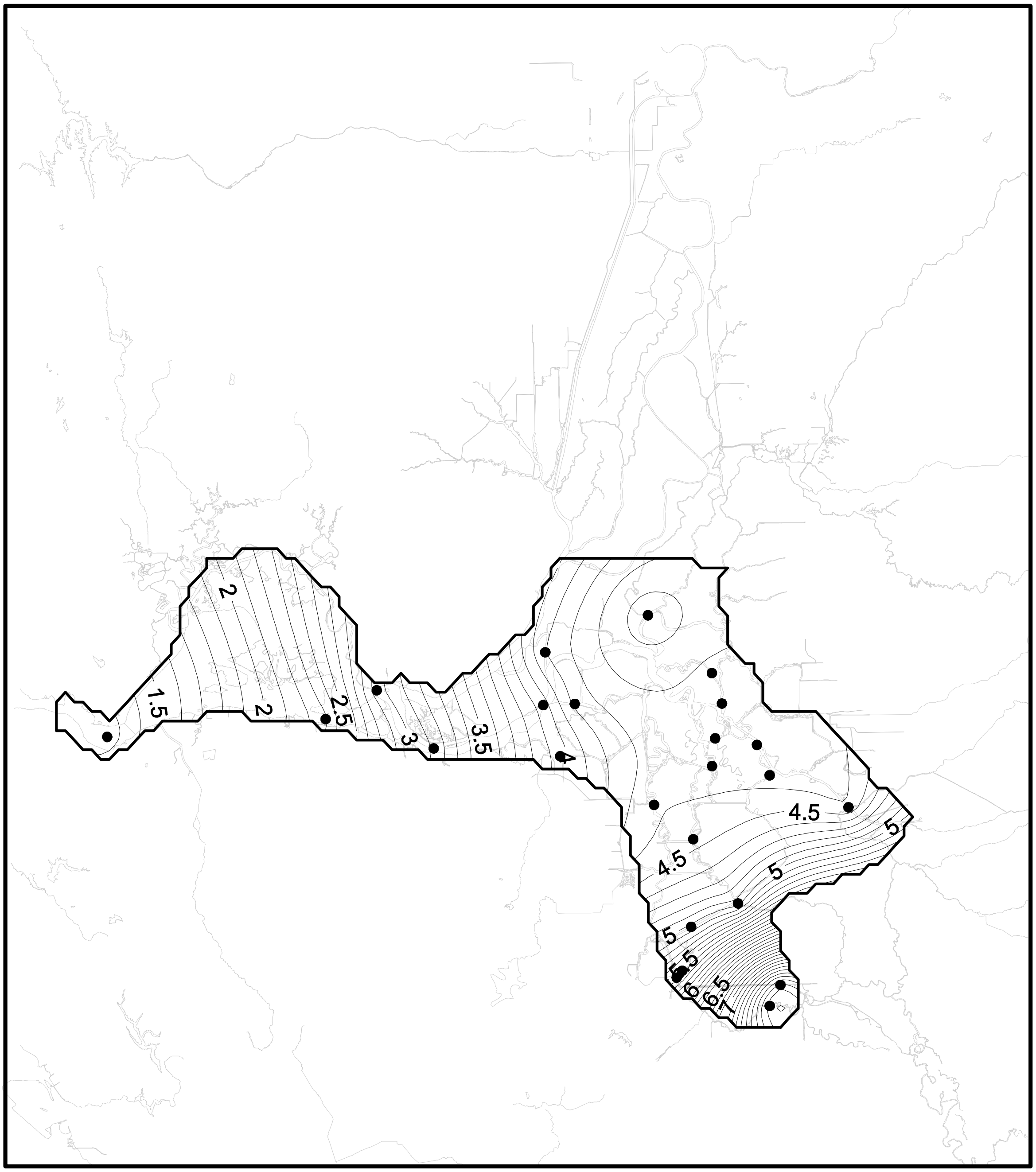


FIGURE V-13

DSM2 RESULTS: 25-HOUR MOVING AVERAGE OF SIMULATED STAGES ON 1/25/1900 FOR SACRAMENTO RIVER CENTERING, 200-YEAR STORM



CHAPTER VI

SUMMARY

This report summarizes the existing hydrodynamic conditions in the Delta during floods. The Delta hydrodynamics were investigated through historical data and computer model simulations. The findings of this investigation are summarized as follows.

1. The Delta is the converging location of tides and inflows from Sacramento River, San Joaquin River, and eastside streams. The hydrodynamic conditions in the Delta are determined by the hydraulic forces of the currents created by these major sources of water in combination with in-Delta tidal conditions.

2. During the 1997 Flood, the coincident high tide conditions and the high flow from Sacramento River dominated the hydrodynamic conditions in the Delta. The flows from San Joaquin River, although high, are less significant to Delta hydrodynamic conditions thatn those from the Sacramento River.

3. UNET and DSM2 were used jointly in the Comprehensive Study to simulate the Delta hydrodynamic conditions during floods. Areas with project levees (one side or both) are modeled by SACUNET or SJRUNET to maintain consistency with other studies in the Comprehensive Study. The remaining Delta was modeled by a reduced DSM2. The modeling area of DSM2 was reduced also because DSM2 has limited abilities in simulating flooding conditions and levee failure. The interfaces between DSM2 and UNET models were facilitated by flows instead of stages because differences in model resolution and basic assumptions exist between these two models.

4. Any simulated hydrodynamic conditions in the Delta are subject to the assumptions associated with the development of concurrent Delta inflows and the downstream boundary conditions at Martinez.

    - The inflows are in term subject to the assumptions used in the SACUNET and SJRUNET, as well as those of the operational models developed for the upper watersheds.

    - Stage boundary conditions at Martinez for synthetic storm events are difficult to develop because tidal ranges are mainly influenced by planetary movements that have little relationship to the recurrence frequencies of flood hydrology. The adjusted tidal ranges in the 1997 Flood are considered representative for the purposes of Comprehensive Study.

- CVP-SWP exports and the consumptive uses in the Delta are considered insignificant. The assumptions would be conservative because the exports provided some relief in the 1997 flood by converting damaging floodwaters to storage in San Luis Reservoir and other beneficial uses.

5. According to the simulated results of the baseline scenarios developed by the Comprehensive Study, the Sacramento River inflows would create a hydraulic barrier during floods that restricts the San Joaquin River and the Middle River from draining water to the ocean. The hydraulic barrier would be further enhanced if high tide conditions occur. As the hydraulic barrier built up near the Georgiana Slough, the Old River becomes the most important conveyance to drain the south Delta inflows. Compared with the Sacramento River inflows, the San Joaquin River inflows have more influences in river stages in the south Delta area, but much less in the central and west Delta.

6. The hydrodynamic conditions in the Delta are highly dynamic. The influence from each controlling factor (inflows, tides, and others) cannot be discussed in isolation f others. Therefore, the boundary of each controlling factor's influence may not be static. Because of these inter-dependent factors, it is unrealistic to study the potential Delta impacts from the upstream improvements on a case-by-case basis. Alternatively, it may be more advantageous to develop the stage sensitivity index with respect to major controlling factors (such as tides, the Sacramento River flows, and the San Joaquin River flows) and use these factors as predicting tools for potential Delta impacts in the evaluation of upstream improvement plans. The sensitivity index can be developed through controlled model simulations where an example is shown in Chapter III.

CHAPTER VII

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